NITROGEN-PHOSPHORUS INTERACTION IN TWO DARK CLAY SOILS FROM HONDURAS

By

CARLOS F. BURGOS

A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA
April, 1967

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to Dr. H. L. Popenoe for his interest, guidance and patience during the course of the investigation.

Appreciation is also extended to Dr. J. G. A. Fiskell for many helpful suggestions and constructive criticisms of the manuscript. Sincere thanks are expressed to Dr. G. D. Thornton for his interest, and constructive criticism of the manuscript.

Appreciation is also extended to Dr. G. J. Fritz, and Dr. T. W. Stearns, for their interest and participation on the Graduate Supervisory Committee and review of the manuscript.

Thanks are extended to Mr. Fred Ward, and Mr. Julio Mérida for helping with some phases of the laboratory work. Thanks are also extended to Dr. A. B. Awan for his help during the early part of the field work.

Gratitude is extended to the Rockefeller Foundation for granting the scholarship which made possible this investigation.

The author also wishes to extend his appreciation to the Center for Tropical Agriculture for providing part of the financial assistance which made this study possible.

Thanks are expressed to Mrs. Martha Gomez for typing this dissertation.

The author wishes to thank his wife for her understanding and encouragement during his years as a graduate student.

TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS ii

LIST OF TABLES v

LIST OF FIGURES viii

INTRODUCTION 1

LITERATURE REVIEW 3

The Effect of Nitrogen on the Absorption of Phosphorus by Plants 3
Phosphorus in Soil Organic Matter 6
The Influence of Wet and Dry Periods and Temperature on the Mineralization of Organic Matter 8
Mineralization of Organic Phosphorus 9
Organic Phosphorus in Soils From Different Regions of the World 12
Micro-organisms and Soil Phosphorus 15
Effect of Liming on Soil Phosphorus 17
Fractionation of Soil Phosphorus 18
Phosphorus Status of Some Tropical Soils 19
Dark Clay Soils of Tropical and Sub-Tropical Regions ... 20
Studies on Soils From Zamorano 21

METHODS AND PROCEDURES 23

Selection of Soil Sites 23
Methods 25
  Preliminary trial 25
  Greenhouse study 27
    Millet experiment 27
    Oats experiment 28
  Laboratory study 29
    Carbon dioxide evolution experiment 29
  Soil characterization 31
Physical Analysis 31
Chemical Analysis 33
Statistical Analysis 35

TABLE OF CONTENTS -- Continued

Page

RESULTS AND DISCUSSION 36

Preliminary Experiment 36
Greenhouse Experiment With Millet 38
Dry matter 38
Nitrogen uptake 45
Phosphorus uptake 49
Organic and inorganic phosphorus content of the soil .. 53
Carbon Dioxide Evolution Experiment 61
Effect of nitrogen application on soil organic phosphorus and carbon dioxide production 61
Effect of phosphorus application on soil organic phosphorus and carbon dioxide production 61
Effects of Rate and Placement of Fertilizer Phosphorus on Dry Matter Yield and Nutrient Uptake of Oats Grown on Soil A 64
Theoretical evaluation of phosphorus placement 65

SUMMARY AND CONCLUSIONS 70

APPENDIX 73

LITERATURE CITED 91

BIOGRAPHICAL SKETCH 97

LIST OF TABLES

Table		Page
1	Yield of dry sorghum forage as influenced by N and P fertilization of two Zamorano soils	37
2	The effect of N and P applications on the yield of dry sorghum	39
3	Dry weight yield of millet plants as influenced by N, P, and K fertilization of two Zamorano soils	41
4	The effect of N, P, and K applications on the yield of millet plants	43
5	Uptake of N by millet as influenced by N, P, and K fertilization of two Zamorano soils	46
6	The effect of N and P applications on the uptake of N by millet	47
7	Uptake of P by millet as influenced by N, P, and K fertilization of two Zamorano soils	50
8	The effect of N and P applications on the uptake of P by millet	51
9	Organic P content in two soils from Zamorano as influenced by N, P, and K fertilization	54
10	The effect of N, P, and K applications on the soil organic P content	55
11	Inorganic P content in two soils from Zamorano as influenced by N, P, and K fertilization	58
12	The effect of N, P, and K applications on the soil inorganic P	59
13	The mean effect of N and P applications on CO_2 production and organic P content of a soil from Zamorano	62

LIST OF TABLES -- Continued

Table		Page
14	The effect of P application on yield and P uptake of oats grown in the greenhouse on a soil from Zamorano	66
15	Phosphorus uptake ratios in relation to fertilizer placement ratios	69
16	Profile descriptions of two Zamorano soils	74
17	Physical properties of soils	76
18	Chemical properties of soils	77
19	Analysis of variance for yield of dry sorghum forage obtained in response to N and P fertilization of two Zamorano soils	78
20	Analysis of variance for dry weight yield of millet plants obtained in response to N, P, and K fertilization of two Zamorano soils	79
21	Analysis of variance for N uptake by millet grown on two Zamorano soils fertilized with N, P, and K	80
22	Analysis of variance for P uptake by millet grown on two Zamorano soil fertilized with N, P, and K	81
23	Analysis of variance for organic P content of two Zamorano soils fertilized with N, P, and K	82
24	Analysis of variance for inorganic P content of two Zamorano soils fertilized with N, P, and K	83
25	The effect of N and P applications on CO_2 production from a Zamorano soil	84
26	The effect of N and P applications on organic P content of a soil from Zamorano	85
27	Analysis of variance for CO_2 production in a Zamorano soil fertilized with N and P	86
28	Analysis of variance for organic P content of a Zamorano soil treated with N and P	87

LIST OF TABLES -- Continued

Table Page

29 Dry weight yield of oat plants as influenced by P fertilization of a Zamorano soil 88

30 Uptake of P by oats as influenced by P fertilization of a Zamorano soil 89

31 Analysis of variance for P uptake by oats grown on a Zamorano soil fertilized with N, P, and K 90

LIST OF FIGURES

Figure		Page
1	Climatic data for 10 years at Zamorano, Honduras	24
2	Locations of sites A and B. A is the field under rotation grazing. B is the field under burning. Scale 1:10,000	26
3	Yields of dry sorghum forage, as influenced by N and P applications	40
4	Yields of dry millet plants, as influenced by N and P applications	44
5	Uptake of N by millet, as influenced by N and P applications	48
6	Uptake of P by millet, as influenced by N and P applications	52
7	Changes in organic soil P, as influenced by N and P applications	56
8	Changes in inorganic soil P, as influenced by N and P applications	60
9	The effect of N and P applications on soil organic P and production of CO_2	63
10	Yields of dry matter and P uptake by oats, as influenced by placement and rate of P application	67

INTRODUCTION

Dark clay soils at Zamorano, Honduras, are low in total N and available P but relatively high in C. Consequently, they have high C/N and C/P ratios. In addition, about 60% of the total P is in the organic fraction. All of the above properties have a very important effect on the response of these soils to fertilizer application.

As in the case of most dark clays, Zamorano soils present tillage problems. Because of their high clay content (30-35%), they are very hard when dry and very plastic and sticky when wet. In Honduras, dark clay soils are mostly used for grazing. However, evidence provided in the literature and by experience indicate a high agricultural potential for these soils when properly managed.

One of the improvements within the reach of the individual farmer is fertilization. With the establishment of fertilizer factories in the countries of El Salvador and Costa Rica, the cost of fertilization in Central American countries is lower than it was in the past when all fertilizers were imported.

The Central American common market provides an ideal situation for the expansion of agriculture because products can be offered to a larger population and therefore large scale production becomes possible and economical.

In recent years, results from fertilization trials made at Zamorano have been encouraging. However, there are still many problems which need further study. One of them is the interaction between N and P in these soils. This is the subject of the present investigation.

The objective of this study was to explain the reason for the NP interaction in two dark clay soils from Zamorano which had not been previously fertilized.

The findings of this research may be applicable to other soils of Central and South America. However, local climatic conditions and special soil chemical and physical properties should be given careful consideration.

LITERATURE REVIEW

The Effect of Nitrogen on the Absorption of Phosphorus by Plants

The effect of applied N on uptake has been studied by many authors. Robertson, et al. (64) found that the addition of ammonium sulfate to a silt loam from Indiana caused a significant effect on early P utilization by corn, and a higher absorption of P by the plant for the remainder of the season. Olson and Dreier (57), working with soils from Nebraska, showed that applied N stimulated the use of fertilizer P by wheat and oats under a wide range of soil conditions. They observed that ammoniacal-N exceeded nitrate-N in this effect during the early stages of plant growth.

Yuen and Pollard (83) reported increased absorption of P by Italian ryegrass treated with repeated applications of nitrogenous fertilizers. They observed that in a soil at pH 4.9, sodium nitrate and potassium nitrate were more efficient than ammonium sulfate and ammonium chloride in increasing the uptake of native and fertilizer P by plants. In soils of pH 6.4, they observed that the ammoniacal sources promoted P uptake by Italian ryegrass. They also compared the ammonium salts of mono-hydrogen orthophosphate and di-hydrogen orthophosphate with ammoniated superphosphate and found that the absorption of P and N increased with increasing N content of these fertilizers.

This seems to indicate that in acid tropical soils, the addition of nitrate-N rather than ammoniacal-N along with fertilizer P would be more advantageous for better use of applied P.

Dormaar and Ketcheson (26) demonstrated that the ammoniacal-N tends to be more efficient than the nitrate-N for influencing P uptake.

The N carrier influenced the availability of fertilizer phosphorus to plants, according to work by Caldwell (18). He showed that salts such as ammonium salts of nitrate, sulfate, and chloride increased P absorption by corn from superphosphate significantly when the nitrogen and phosphorus sources were intimately mixed. He also reported that the N from ammonium phosphate and ammoniated superphosphate increased the P absorption. However, when calcium nitrate and sodium nitrate were mixed with superphosphate, there was no increase in P absorption. He concluded that the effect of N on P absorption was caused by chemical interactions between N and P salts rather than physiological effects of N in the plant.

Working with sandy loam soils from Tanganyika, Kabaara (44) also reported a N and P interaction. He concluded that phosphate enhanced uptake of nitrates.

Bouma (13) studied the effect of prolonged applications of ammonium sulfate on a soil from Australia utilized for citrus. He found that applications of phosphate caused a marked increase in growth and P uptake only of plants growing in soils which did not receive N fertilizer. He concluded that Al released by the acidity generated in the soil by ammonium sulfate fixed the added phosphate in the N plots. On the other hand, without applied N phosphate fixation was not found and a response to applications of phosphate were obtained.

Rennie and Soper (63) concluded that the difference between the effect of ammonium ion and nitrate ion on P uptake was due to an indirect effect of the former on the ability of the plant to take up P. They believed that the availability of applied P was not altered by the presence of ammonium ions.

Hardy (34) conducted greenhouse tests on five different soil types from Trinidad which had been utilized for growing sugar cane. They obtained an increase in yields of sudangrass with increasing rates of superphosphate when high N application were made. The optimum rate of superphosphate was about 1,130 kg/ha. He suggested that in the past the application of fertilizers at low rates explained the lack of response to soluble phosphatic materials.

Miller and Ashton (52) obtained increased absorption of P by oats with increasing rates of N. The increase of fertilizer-P absorption was much greater than the increase in dry weight of tops. Wheeler (82) obtained significant increase of oven-dry grass by application of superphosphate only where N at the rate of 291 kg/ha/year had been applied.

The increased absorption of P from the fertilizer caused by N applications has been explained by Grunes (31) in terms of the binding mechanism of plant roots. He attributed part of the interaction to the failure of applied N to promote the absorption of the difficultly soluble soil P.

Bennett, et al. (10) believed that the increase in P content of leaves with N applications was associated with the physiological stimulation of the plant rather than with increased solubility of P or more extensive root system. Cole, et al. (20) reported that pretreatment with N fertilizer stimulated P content of the roots. They found that high P applications showed less effect than the N pretreatments. They indicated that the greater stimulation of P uptake at higher P applications resulted in a higher proportion of fertilizer P to soil P taken up by plants when N is applied. This behavior was consistent, they found, with the observations of little or no increase of total P absorbed by plants when N was applied to soil having a low P content.

In a study on the influence of N on the availability of fertilizer P in two alluvial soils, Dev (23) found that N significantly enhanced the plant uptake of fertilizer P.

Development of a root mass in the area of nitrogen and phosphorus placement has been observed by Miller and Ohlrogge (53). They indicated that the increased P uptake was independent of the soil-P level. The effect of N on the availability of soil and fertilizer P was the subject of an extensive review of Grunes (30). He suggested that the addition of N to a soil deficient in N increased the absorption capacity of roots more than could be accounted for by an increase in weight of the roots. In the same review, he noted that N increased the growth of tops more than roots. This effect was also reported by Dormaar and Ketcheson (26). They found that the total dry matter of roots was inversely related to the N application and to total P uptake. In the same paper, they found that the effect of N and P uptake was enhanced by increases in soil temperature.

Phosphorus in Soil Organic Matter

Broadbent (16) pointed out that although soil organic matter contained less P than N in many soils it is responsible for more than half of the total P in the soil. He mentioned that P compounds present in soil organic matter are: the inositol phosphates, nucleic acids and their derivatives, and phospholipids. In the same article, he explained that large organic C to organic P ratios resulted in immobilization of available P. On the other hand, if the C/P ratio is small, a net increase in inorganic P is produced.

Barrow (8) reviewed the work on P in soil organic matter and suggested that the organic P must be regarded as a variable rather than as a characteristic fraction of soil organic matter. He pointed out that several authors had compared the decrease of organic P with the decrease of the other constituents, but the results showed little agreement. With soils from South Australia, the organic P content fell more slowly than the N content. Similar observations were noted with soils from Iowa, Colorado, and Texas, but the rate of mineralization increased with increasing temperature. In British Guiana, little difference in the relative rate of decrease of N and P was observed. In Ghana soils, C and organic P decreased at a similar rate, but N decreased more slowly. From this, he concluded that the rate of mineralization of organic P sometimes was not necessarily the same as the rate of mineralization of C or N.

The low content of organic P in soils was not characteristic of severe soil P deficiency, according to Barrow (8). The organic matter formed when clover was fertilized with superphosphate did not show an increase in P content. Barrow concluded that there are two types of evidence which indicated that not all the organic P was intimately connected with the organic matter of the soil. These are (1) unlike

C and N, all the organic P can be extracted from soils by alkaline colutions, and (2) phosphorus does not seem to occur in organic matter in any characteristic proportion.

The conclusion can be drawn from (2) that the content of other mineral elements in the soil may influence the production of organic matter of different chemical composition. Thus, the composition of organic matter varies from one region to another.

The Influence of Wet and Dry Periods and Temperature on the Mineralization of Organic Matter

Russell (66) indicated that an important factor which controlled the rate of mineralization of the organic P was the number of times the soil was dry or moist. Temperature was the other factor, he found, because the warmer the soil temperature was, the faster the rate of decomposition of organic matter occurred. Russell also indicated the importance of the organic matter in some tropical soils which have most of their potentially available phosphate in the organic form.

In some areas which experience a dry and wet season, the mineralized and the organic fraction of N do not function in close interdependence. Jones (41) observed that the increase of nitrate in the top 30 cm took place long before the rainy season, although a further increase was observed following the rains. Later, Jones (42) conducted studies on the C of the irrigated soils of the same area, which was the Sudan Gezira, and concluded that the dry period was one of intense microbiological activity. He (43) also noted that here the organic-N reached a maximum during the rainy period of July to August and decreased to a minimum during the dry season of March to April. He reported that the organic-N in this soil varied from 215 ppm to 229 ppm and that the nitrate-N was only a few ppm.

The time of application of nitrogenous fertilizer to a crop grown in areas characterized by pronounced wet and dry seasons was studied by Bruce and Tyner (17). They obtained the maximum response to N applied to the dry season crop when all the N was applied in the row at planting time. For the wet season, the greatest N response was obtained by splitting the N application as follows: one-fourth in the row at planting time, one-half top dressed four weeks after planting and one-fourth top dressed seven weeks after planting.

Mineralization of Organic Phosphorus

Russell (66) indicated that probably none of the phosphate compounds present in organic matter were directly available to the plant. He indicated that C/P ratios of 100 to 200 in soils low in phosphates may result in the immobilization of inorganic or available phosphate in the process of humus formation. He also stressed that more work had been done on organic P mineralization than on its immobilization due to humus accumulation.

Thompson, et al. (74) conducted some studies on the occurrence of mineralization of organic P and reported that organic P mineralization was positively correlated with organic N and C mineralization. They also observed increased organic P mineralization with increasing soil pH during laboratory incubation and soil development in the field.

Nye and Greenland (55) found that a forest soil containing 50 ppm of organic P and savanna soil with 20 ppm of organic P released 9 and 3.5 kg of P/ha in one year, respectively.

The hypothesis that P which is present in soil in the organic form at the beginning of a season would be of significance in the nutrition of plants grown during that season has been tested by Van Diest and Black (77). They found a correlation between several soil availability indices and the soil organic P extracted by a solution made of 1% potassium carbonate and 2% sodium hydroxide and subsequently hydrolyzed by hypobromite. This correlation was significant only for the soils in the range of pH 5.5 or above and at temperatures of 20 and 35C. These authors (78) also measured the amount of organic phosphorus mineralized during incubation.

Goswami and Datta (29) studied the effect of incorporating two types of plant material at two moisture levels on the rate of decomposition of both native and added organic matter. They investigated the availability of N, P, and K. They did not find any organic P after 30 days of incubation; but after 46 days, they found an increase of organic P. After 63 days, the organic P decreased. They explained these changes on the basis of P immobilization in soils. They considered that during the first phase, micro-organisms mineralized the organic P of the added organic matter. This, they expected, with materials of C/P ratios lower than 200; micro-organisms probably used the available P for their metabolism. In the second stage, they postulated that an increase in the population of micro-organisms resulted in the immobilization of the inorganic P released in the first stage. Later, a decrease of organic P possibly represented the mineralization of the organic P from the dead microbes. However, they pointed out that microbial fixation could not account for the decrease of available P observed in the experiment. They concluded that the rate of decomposition of organic matter was determined by the C/N and C/P ratios and that small additions of organic matter stimulated the decomposition of native organic matter. This resulted in a larger net-C loss from the soil. The stimulation lasted while the added material formed an important part of the decomposing organic matter in the soil.

Sengupta and Cornfield (69) studied the mineralization of organic P in calcareous soils. They reported that sodium phytate was more stable in soils having a higher calcium carbonate content. This was due to the lower solubility of the calcium phytate in the presence of Ca ions. They observed that a rapid initial mineralization of organic P was followed by a slower rate of mineralization. The authors attributed this effect to wetting of the air-dried soil. Upon wetting, the metabolic activity of the soil microbes increased and rapid dephosphorylation resulted. Later, the soil was depleted in energy-supplying material needed for microbial activity and consequently the rate of mineralization decreased. They also indicated that the greater the amount of soluble P present in the soil, the less mineralized P would be used by the micro-organisms. Nye and Bertheux (54) observed that litter of forest soils released N and P at the same rate. However, in savanna soils, litter released mineral P more rapidly than mineral N. They pointed out that in savanna soils, mineralization of soil organic P compounds proceeded at the same rate as that of the bulk of the soil organic matter.

Organic Phosphorus in Soils From Different Regions of the World

Nye and Bertheux (54) studied the distribution of P in forest and savanna soils of the Gold Coast and reported a close correlation between organic P and organic C content. They found C/P ratios of 233 and 247 for the organic matter of forest and savanna soils respectively. Since the average C/P ratio for a range of mineral soils throughout the world is about 110, they suggested that high C/P and N/P ratio were characteristic of P deficient soils. They indicated that Bray's acid F extractant provided a better indication of phosphate response than the more complete extractions. They also found resting fallow increased readily soluble P.

Bates and Baker (9) studied the distribution of P in the profile and in various soil fractions of a Nigerian forest soil. They indicated that the top soil was high in total P content which decreased steadily to 75 cm of depth and increased to 100 ppm at 120 to 180 cm. They observed that the C/P ratio of worm casts was 153 in the surface soil but dropped to 44 below this depth. Litter contained 900 ppm of total phosphorus of which 697 ppm were organic.

Patel and Mehta (51, 59) investigated with 21 soils from India and found a significant positive correlation (r = + 0.6384) between the P extracted with 1% potassium carbonate and dephosphorylated by hypobromite and the uptake of P by sorghum plants. However, this correlation was not considered important since there was no established relationship between organic P content of the soils and the uptake of P by plants. Moreover, the organic P of these soils was barely 2% of the total soil P.

Kaila (45) conducted studies of organic P in 213 Finnish soils. Phosphorus content ranged from 100 to 940 ppm with an average of 340 ppm of P. The range found corresponded to 17 to 68% of the total P content. He observed that clay soils tended to be richer in organic P than soils of coarser texture, but poorer than the humic soils. He did not find any close relationship between organic P and C content. The C/P ratios ranged from 61 to 276 in the cultivated mineral soil, from 141 to 526 in the humus soil, and from 67 to 311 in the virgin soil. He found a significant correlation between the content of organic P of clay and humus soils and the content of acid-oxalate soluble aluminum. In Finnish soils, the accumulation of P in the organic form was favored by the long cold periods and by the presence of Al and Fe in acid soils.

The organic P of 18 representative soil types from New Zealand ranged from 59 to 87% of the total P; the average was 75% according to Martin (48). He showed that the binding of inorganic and organic P in the soil were separate and distinct processes. The organic P was more readily extractable by dilute potassium hydroxide than was inorganic P.

John, et al. (40), working with 38 soils which were representative of mineral soils occurring in Canada, found an organic P content ranging from 21 to 802 ppm. This constituted from 1.8 to 77.7% of the total P in the soil. They reported a close dependence of organic P on N in the soil. The C/P and N/P ratios reported by the authors ranged from 46 to 648 and from 5.46 to 57.6, respectively. They interpreted these as the variability of the organic P in the soil organic matter. Using the multiple correlation technique, they found N and pH as the only variables accounting for the variation in the organic P content of a wide variety of soils. Soil C had no direct relationship with soil organic P and therefore was not a limiting factor for the accumulation of organic P. No shortage of total or available P for the microbial immobilization of P was evident. They believed that the variations in levels of N and pH influenced the form and stability of organic P.

Hawkins and Kunze (38) conducted similar studies on four Grumusols from Texas. They indicated that response to applied P had not been appreciable on the Victoria and Houston Black soils. They reported that these soils had C/P ratios below 100 in the A horizon and suggested that the low C/P ratios were favorable for crop use of the mineralized organic P. They found larger responses to applied P on the Beaumont and Lake Charles soils which are Grumusols, also. The two latter soils, they found, contained C/P ratios two to six times larger than those for the Victoria and Houston Black soils. This meant a proportionate reduction of organic P which can undergo mineralization. They suggested that for soils low in total inorganic P, previous knowledge of the C/P ratio or some measure of the contribution made by the organic fraction would contribute to soil test recommendations.

Dahnke and co-workers (21) found less than 500 ppm total P in some soils from El Salvador. However, Regosols, Lithosols, and Alluvial soils contained up to 1,100 ppm total P. A great proportion of this was organic and readily available P. In Latosols and Grumusols almost all the P was found as occluded iron phosphate or in unweathered minerals. Malavolta, et al. (47) reported that the organic P in soils from São Paulo, Brazil, ranged from 82 to 1 ppm. The total P ranged from 978 to 123 ppm.

Bornemisza (12), in a recent review of 40 papers, indicated that temperature, pH and alternate wetting and drying affected P mineralization. Synthesis of organic P occurs between pH 5.5 to 7.5 and is increased by wetting and drying. An increase in pH enhanced mineralization.

Bornemisza (12) explained that the total P content or organic matter was important in mineralization. A content higher than 0.2% resulted in a rapid mineralization, while at lower content of P immobilization occurred, possibly due to synthesis of organic matter. He also pointed out that allophane why? made the mineralization of organic P very difficult and that organic P of virgin soils mineralized more easily than organic P of cultivated soils. He indicated that additions of N and inorganic P increased the mineralization of organic P.

Micro-organisms and Soil Phosphorus

Hardy and Hewitt (37) conducted studies on the nitrification of some representative sugar-cane soil profiles of British Guiana. They concluded that the failure to nitrify more efficiently was due to the absence of the nitrifying organisms. They considered the possibility that the marked P shortage of these soils accounted in part for the low nitrifying capacity observed; this was because soil micro-organisms needed abundant soluble P to grow and multiply. The P deficiency, however, was not considered to be the critical factor in their studies.

Swaby and Sherber (73) indicated that rhizosphere micro-organisms appreciably increased the availability of mineral or sorbed P under certain conditions. They noted increased microbial effect in acid sandy soils, old pastures rich in micro-organisms and humic acid, and coarse textured soils which were low in sesquioxides but high in organic matter and sulfates. They concluded that decomposition of organic P by microbial action increased their availability to plants except when large amounts of carbonaceous material were present; in the latter case, P was temporarily retained in microbial cells. They found that out of 20 organic phosphates tested in the soil, all were good P suppliers except ferric phytate which was fair and soil humic acid which was poor.

Roche (65) studied the effect of various insoluble phosphates on the micro-organisms of the soil. He found physiological stimulation by addition of phosphate on the nitrogen-fixing, nitrifying, denitrifying, cellulolytic, amylolytic and sulfate-reducing microbes.

In P deficient soils, increased responses in N fixation after additions of phosphate were found by Sen, et al. (68). They attempted to find out if there was any relationship between N fixation by Azotobacter in 19 soils from India and their contents of available P as determined by three methods. They found a positive correlation $(r = + 0.587)$ between N fixation and P extracted with 1% citric acid. The other two methods did not show any relationship between P extracted in N fixation by Azotobacter.

Das (22) reported similar work to the above using soil fungi. He used 18 fungi isolated from a soil of a paddy field and found nine fungi to be strong utilizers of all the insoluble phosphates supplied to them. Among them were Aspergillus niger, Penicillum tardum, and Sclerotium rolfsii. Four organisms were found to prefer some insoluble forms. Three of these appeared to be weak utilizers, and the remaining two did not produce appreciable amounts of dry matter in any of the media employed. He pointed out that these fungi incorporated P from insoluble sources into their bodies and formed organic P compounds; upon decomposition of these compounds after death of the cells, P might be released in an available form to higher plants. He stressed that this hypothesis needed more study.

Rao, et al. (62) assessed the efficiency of P solubilizing organisms. They used phosphobacterin, a bacterial fertilizer containing *Bacillus megatherium* var. *phosphaticum* obtained from the Soviet Union, and an Indian strain identified as *Bacillus megatherium* in laboratory pot tests and field studies. They found that in the sterile series both phosphobacterin and the Indian strain were equally effective. In the unsterilized series, the Russian strain was more effective than the Indian strain in solubilizing phosphate added in the fertilizer. Phosphobacterin was better than the Indian strain with respect to fertilizer P uptake by the plant. A significant increase in the uptake of native phosphorus was not found, by either of the two bacterins.

Effect of Liming on Soil Phosphorus

Hardy (34) showed that highly acid soils benefited from liming and gave a much enhanced P effect. He recommended for Trinidad soils that the effect of high P treatments should be combined with high N levels on both unlimed and limed soil. Similar results of the effect of liming on the uptake of P by plants have been reported by Rai, et al. (61). They suggested that the P extracted by Bray's solution was not affected by liming. They found an increase in the P concentration of the leaves due to liming. They also reported yield increases due to liming of acid soils. The increased uptake of P by plants was further increased by the application of phosphatic fertilizers to the soil.

Awan (4) showed that after two year of cropping, liming enhanced the mineralization of organic P. He found that this conversion resulted in a significant increase in yields of corn, sorghum, beans and green manure. However, Yuen and Pollard (83) reported that liming decreased the uptake of P and N when fertilizers of high ammoniacal N were applied.

Fractionation of Soil Phosphorus

Patel and Mehta (58) studied the correlation between P uptake by plants and soil P extracted by different solutions. They obtained a positive correlation (+ 0.4829) between P extracted by 0.1 N hydrochloric acid and plant P uptake. They did not find a significant correlation between organic P and available P. They obtained a significant correlation between absorpted P and soil P extracted by dilute carbonate. A high correlation coefficient ($r = + 0.8341$) was obtained in their work between absorpted P and P uptake by sorghum plants.

Al-Abbas and Barber (1) reported similar work. They used 24 soils classed as Grey-Brown Podzolic and Humic-Gley soils. The iron phosphate fraction of the soil was more highly correlated with plant available P than any other P form in the soil. They developed a soil test based on the above findings (2).

Saxena (67) outlined a procedure for the extraction of organic P from the soil. He compared his procedure with several well-known methods and indicated the advantages of the proposed method. He used a pre-extraction with concentrated hydrochloric acid followed by an extraction with 1.5 N ammonium hydroxide at 75C for two hours and 0.5 N sodium hydroxide at 90C for six hours.

Martin (48) developed a method for extracting and partially fractionating soil organic P in New Zealand soils. The method consisted of three sequential extractions of one hour each at room temperature with 0.3 M potassium hydroxide following an acid pretreatment. This method extracted 85% of total organic P. In his method partial fractionation of organic P was achieved using a strong anion-exchange resin (Dowex 1).

In another paper, Martin (49) demonstrated that the method provided quantitative data on the transformation of soil inorganic and organic P.

Martin (50) also applied the extraction and resin fractionation procedures to a study of representative soil types of New Zealand. He reported that analyses from plots without P and those with high P in a fertilizer trial indicated that the extraction and fractionation procedures would be valuable for studying the transformation of fertilizer P into soil organic P only in trials of long duration.

Bornemisza (12) reviewed the existing methods for determining organic P and stressed the existence of a method for direct determination of organic P after absorption by activated charcoal.

Phosphorus Status of Some Tropical Soils

Hardy (36) assessed the P level of some British Guiana soils by pot tests. He demonstrated that markedly beneficial responses to P fertilizer and to lime application were found when materials were properly selected and applied. He also suggested that the efficient utilization of added N fertilizer depended on an adequate phosphate, calcium and soil reaction status obtained by previous treatments.

In a similar study with some West Indian soils, Hardy (35) showed that volcanic soils were deficient in available phosphate. As in his previous study with British Guiana soils, he found a good response to generous applications of P fertilizer provided that abundant N was present in available form or added as fertilizer.

Malavolta and associates (47) have shown that in soils of the state of São Paulo, Brazil, only a small portion of the soil P was available to plants. He stated that this explained the frequent responses obtained in the field to application of P fertilizers.

Awan (4) obtained significant increases in yields of corn, sorghum, beans, and green manure due to addition of superphosphate. In his study N was added to all treatments.

Dark Clay Soils of Tropical and Sub-Tropical Regions

A summary of the available knowledge on dark clay soils has been published recently by the Food and Agriculture Organization of the United Nations in a monograph edited by Dudal (28). This monograph cited the general characteristics, distribution, use, management, productivity, and classification of dark clay soils.

Dudal (27) indicated that dark clay soils appeared in the literature under different names. He found 40 names. In the United States these soils are known as Grumusols or Vertisols according to the 7th approximation (72). He indicated that these soils occurred in all five continents. Major areas of these soils occurred in Africa and Asia, they were widespread in Central and South America but information on their distribution in these areas was very limited.

According to D'Hoore (25), several African soils showed all the morphological characteristics of Vertisols but amorphous clays were dominant.

Studies on Soils From Zamorano

Sierra (70) studied the Ap horizon of three soil types from Zamorano, Honduras, for cation exchange capacity which ranged from 16 to 21 meq/100 g of soil. He found the total soil P was from 210 to 120 ppm; organic matter was from 3 to 4%; pH from 5.35 to 5.85; and clay from 20 to 29%. He extracted soil P by eight different extracting solutions and used different lengths of time and length of shaker strokes. For Zamorano soils, the mixture of 0.05 N hydrochloric acid plus 0.025 N sulfuric acid extracted the most P. The range of P extracted was from 0.3 to 8.0 ppm of soil.

Awan (4) reported significant increases in yields of corn and green manures due to liming and P fertilization of Zamorano soils. He concluded that liming favored the conversion of organic P to inorganic P. The organic fraction of P in the soils studied represented 84% of the total P. Other studies by the same worker (7) showed that fertilization of the soil with muriate of potash tripled the yield of potatoes. When P was applied as triple superphosphate, a similar increase in yield was obtained. When the soil was fertilized with a complete fertilizer, the production of potatoes went from 6 tons/ha of the check plot to 32 tons/ha. The average potato yield in Honduras is 2 tons/ha.

He indicated the importance of using certified seed and the control of pests for obtaining high yields. Awan (6) found fertilization with muriate of potash significantly increased the yield of a hybrid corn suceptible to lodging, but in another hybrid the only effect was a reduction in lodging.

Mulching increased potato yields in Zamorano, according to Awan (5). He obtained a 27% increase in yield by applying 2.5 tons/ha of Jaragua straw to the surface of the soil and a 35% increase due to a mulch of 5 tons/ha. He attributed this increase to a decrease in soil temperature of 6 to 7C caused by mulching.

METHODS AND PROCEDURES

Selection of Soil Sites

Two soils from the Zamorano valley in Honduras were chosen for study. The valley is located at latitude 14° 0' north and longitude 87° 2' west, 22 miles southwest of Tegucigalpa, capital city of Honduras. The Zamorano valley has a tropical climate with monthly average temperatures below 24C and an average annual rainfall of 1,086 mm falling between the months of May and November. The average monthly rainfall, the mean, average maximum and minimum monthly temperatures, and the calculated evapotranspiration for the period 1959 to 1965 are presented in Fig. 1. The evapotranspiration in millimeters (mm) was calculated by multiplying the mean monthly temperature in degrees centigrade (C) by 4.98. The method followed that given by Holdridge (39).

Two sites, A and B, were selected. Neither site had received fertilizer applications in the last 20 years. The sites were located no further than 100 m apart. The topography of both sites is undulating with a slope of 4 to 5% toward the southwest. The vegetation of site A is a permanent pasture composed mainly of grasses of the genera *Paspalum* and *Hyparrhenia* and small voluntary legumes. Rotation grazing is the type of management practice used on this field. Savanna consisting of Jaragua grass (*Hyparrhenia rufa*) and thorn-scrub (*Prosopis* sp) is the vegetation of site B. In this field burning has been practiced for the

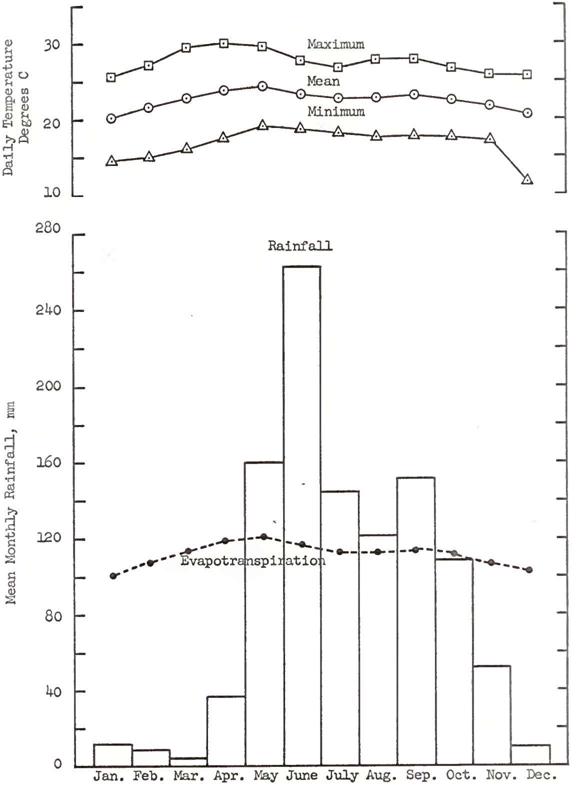

Fig. 1 - Climatic data for 10 years at Zamorano, Honduras.

last 20 years. Because no description of these soils was available, a study of their profile, chemical and physical characteristics was made. The methods for characterizing these soils are described below. Results of this characterization are discussed later in the text. The sites were selected so that soils A and B had similar morphological characteristics but were under different management practices. The locations of sites A and B are shown in Fig. 2.

Methods

Preliminary trial

Surface soil samples to a depth of 15 cm were collected from sites A and B. The sampling was done during the month of February, 1964, before field B was burned.

Three different pits were dug on each site and the samples thoroughly mixed into a composite sample. The soil samples were passed through a 2.0 mm sieve before placed in bags.

Twelve black plastic bags were filled with 2.4 kg of soil from site A and twelve similarly filled with soil from site B. The edges of the bags were rolled down in such a way that a distance of about 3.0 cm separated the surface of the potted soil and the edge of the bag. Soils treatments were: 0 and 100 kg N/ha in the form of chemically pure urea, and 0 and 80 kg P/ha in the form of reagent grade potassium di-hydrogen orthophosphate. Treatments were arranged in a 2 x 2 x 2 factorial randomized block design with three replications.

The soil from each bag and the solid salts were mixed carefully. The mixture was then returned to the bag and tap-water was added to bring

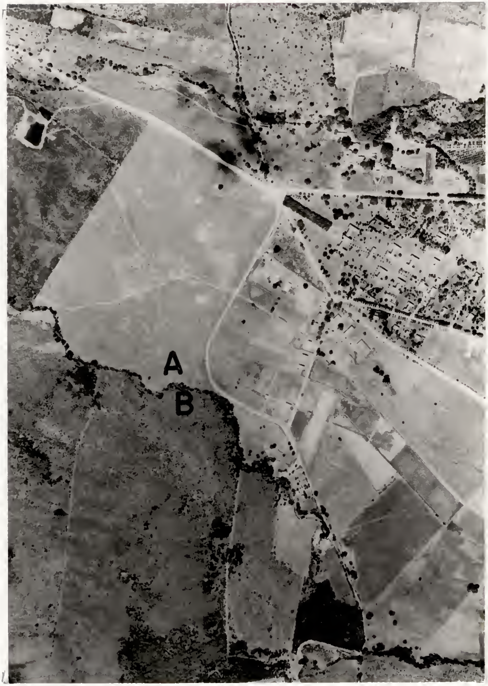

Fig. 2 - Locations of sites A and B. A is the field under rotation grazing. B is the field under burning. Scale 1:10,000.

the soil to nearly field capacity (25%). The bags were placed on a bench. The soil was allowed to come to equilibrium for a week before planting. Water was added every other day.

On March 24, 1964, 20 seeds of sweet-sorghum were planted in each pot. After germination, the number of plants was thinned to eight plants per pot. The eight plants left were harvested on July 4, 1964, 102 days after planting. The harvested plant material was dried at 70C for 24 hours and weighed. These data were analyzed statistically.

Greenhouse study

Millet experiment -- During the month of July, 1964, surface soil samples to depth of 15 cm were collected from sites A and B, air dried, passed through a 2.0 mm sieve, and brought to the University of Florida for greenhouse studies **after fumigation with methyl bromide.**

A 2 x 2 x 2 x 2 factorial (N, P, K, and soils) experiment was conducted from April, 1965, to September, 1965.

The levels of nutrients used were: 0 and 100 kg N/ha in the form of ammonium nitrate, 0 and 200 kg P/ha in the form of sodium di-hydrogen orthophosphate, 0 and 80 kg K/ha in the form of potassium chloride.

The salts used as sources of N, P, and K were mixed with the soil as described for the preliminary trial. The treated soil was put into green plastic pots. Drainage holes at the bottom of the pots were sealed both inside and outside with plastic tape to avoid leaching. Each pot contained air-dry soil equivalent to 2,140 g of oven-dry soil which filled the pot up to two cm from the top; 500 ml of distilled water were added to each pot and the system was allowed to reach equilibrium for 24 hours before the seed was planted. Fifteen seeds per pot of Star millet were planted on April 4, 1965. Later the plants were thinned to 10 plants per pot. Each pot received 250 ml of water every second day. Later, water was added as needed to compensate for the greater use by the larger plants.

The plants were clipped twice. The first clipping was made 32 days after planting. The second clipping was made 66 days later. Fresh and dry weights of the plant material were recorded. Dry weight was measured after drying the material in the oven at 70C for 24 hours. After the second clipping the pots were emptied and the roots separated from the soil by passing the soil through a 2.0 mm sieve. Root samples were washed with deionized water to remove soil particles and dried in the oven at 70C for 24 hours and the dry-weight recorded. Yield data from this experiment were analyzed statistically.

The pots were planted again on August 6, 1965. No additional treatments were applied this time. Harvest was made 53 days later. The dry-weight of the tops was recorded. The plant material harvested from this planting was discarded because of its paucicity. Plant samples obtained from the first planting were saved for chemical analysis. Soil from the pots was sampled in October, passed through a 2.0 mm sieve, and saved for chemical analysis.

Oats experiment -- A second pot test experiment was carried out with soil from field A. This soil was collected in July, 1964, and was treated as described above.

This experiment consisted of 12 pots, each containing an amount of soil equivalent to 2,000 g of dried soil. The treatments applied to the soil in the pots were: 0, 40, 120, 240 kg P/ha mixed with the entire volume of the soil, 40 kg P/ha mixed with 1/3 of the soil volume and 120 kg P/ha mixed with 1/2 of the soil volume. A basal treatment of 100 kg N/ha and 200 kg K/ha was applied to each pot.

The sources of N, P, and K were: ammonium nitrate, sodium dihydrogen orthophosphate, and potassium chloride. All were reagent grade salts.

The amounts of salt needed were mixed with the soil from each pot in the same manner as described for the preliminary trial. Enough distilled water was added to each pot to bring the moisture content to about 25%.

Twenty seeds of oats per pot were planted on December 29, 1965. Distilled water was added every other day to bring the moisture content of the soil to 25% approximately. After germination, the plants were thinned to 10 plants per pot. The tops and roots of the plants were harvested 64 days after planting. Roots were washed and all plant material was dried at 70C for 24 hours. Yields of oven-dry weights were recorded from two replications of each treatment arranged in a randomized block design. Plant material was saved for P analysis.

Laboratory study

Carbon dioxide evolution experiment -- The effects of added P and N on the biological activity of soil from field A were studied in the laboratory.

The soil was dried, passed through a 2.0 mm sieve and mixed. An amount of air-dried soil equivalent to 200 g of oven-dried soil was placed into 12 Erlenmeyer flasks of 500 ml capacity. Fifty milliliters of distilled water were added to each flask. A randomized block design with two replicates was used in this experiment.

The following treatments were applied: check, 100 kg N/ha, 80 kg P/ha, 100 kg N/ha plus 80 kg P/ha, 200 kg N/ha plus 80 kg P/ha, and 100 kg N/ha plus 240 kg P/ha.

The apparatus for determining CO_2 consisted of a series of 12 units. Each unit consisted of an Erlenmeyer flask equipped with a T-shape connecting glass tube extending to the bottom of a 20 ml glass vial containing 0.5 N sodium hydroxide.

Air from a compressor was supplied to these units after it had been passed through three suction-flasks, one containing a solution of 20% sodium hydroxide, the second containing a solution of 4% boric acid and the last one containing distilled water. This was to provide moist air free of CO_2 and NH_3 to the incubating flasks.

This series of reaction flasks was placed in a constant temperature room maintained at 25C.

The liberated CO_2 was absorbed in 0.5 N sodium hydroxide. A solution of 2 N barium chloride was then added to precipitate the CO_2 as carbonate. The excess sodium hydroxide was titrated with 0.1 N hydrochloric acid, using phenolphthalein as the indicator. The total amount of CO_2-C evolved during the experiment was calculated by multiplying the amount of sodium hydroxide, in meq, neutralized by the CO_2 evolved by six. The method is a modification of the method described by Clement, et al. (19). These data were statistically analyzed.

After 16 days of incubation, the flasks were covered with Al foil and stored in the refrigerator at 4C to minimize any microbial activity. Soil from the flasks was chemically analyzed.

Soil characterization

During the month of August, 1965, the soils of sites A and B were characterized in the field. Three pits per site were dug up to a depth of 180 cm and field determinations for pH, color, texture and structure were made. At the same time, undisturbed core samples were collected from each horizon with a 5 x 3.5 cm cylinder for bulk density measurements. The soil core sampler yielded a cylinder of soil of 70.38 cm^3.

Samples obtained from the different horizons with a long knife were air-dried, passed through a 2.0 mm sieve, placed in cloth bags, and brought to the University of Florida for chemical and physical analyses.

Physical Analysis

The samples collected in the field were analyzed in the laboratory for texture, sticky point, index of texture, bulk density, particle density, and soil porosity determinations.

Determination of sand, silt and clay content was made by the standard Bouyoucos method (14).

Sticky point was determined by the hand-kneading process. The value coincides approximately with the field capacity of a soil.

Index of texture is believed to furnish an approximate measure of the capillary pore space or, in other words, of the amount of moisture that can be held by the colloidal components of the soil (33). This determination involves two measurements: sticky point moisture content and content of sand. With these values the index of texture was calculated by subtracting 1/5 of the sand content from the sticky point moisture content. For this determination it is assumed that 20% of the mass of the sand content gives a measure of the quantity of water occurring as films and wedges.

Undisturbed core samples from the different horizons were obtained by driving the cylinder horizonally into the soil until it was filled with the soil. The sampler and its content were removed carefully with the aid of a long knife. The soil extending beyond each end of the cylinder was trimmed flush with the cylinder. The soil was then transferred to a tared dish, dried at 105C overnight, and weighed. The bulk density was determined by dividing the oven-dried weight of the core sample by the volume of the sample.

Particle density was determined for each horizon of a representative soil profile. Approximately 10 g of finely ground, oven-dried soil were placed in a tared 50 ml pycnometer. The pycnometer was then half filled with xylene, washing into the flask any soil adhering to the inside of the neck. The entrapped air was removed by placing the pycnometer and its content in a vacuum desiccator. The desiccator was connected to a vacuum pump and a partial vacuum created for 15 minutes.

The stopcock of the desiccator was closed the pump was disconnected, and air was allowed to move back into the desiccator by gradually opening the stopcock.

The pycnometer was removed from the desiccator and filled with xylene. The ground glass stopper was inserted in the pycnometer. The outside of the flask was dried and cleaned thoroughly with a dry cloth. The pycnometer was then weighed. A tared flask was used to determine the weight of 50 ml of the xylene at room temperature. The particle density was calculated by dividing the weight of the dry soil by the weight of the xylene displaced. The method was a modification of the standard pycnometer method as described by Blake (11).

Total porosity was calculated using the ratio of bulk density to particle density of the soil and subtracting this from unity. Percent pore space was obtained by multiplying this value by 100. The method followed the procedure given by Vomocil (80).

The percent capillary pore space was derived by multiplying the index of texture by the bulk density of the soil. The method followed that given by Vine (79).

The non-capillary pore space was assessed by subtracting capillary pore from total pore space.

Chemical Analysis

Organic C in the soil was determined by the Walkely-Black wet-combustion method as modified by Walkely (81). One gram of air-dried soil was oxidized with potassium dichromate and sulfuric acid. With orthophenanthroline as an indicator, the excess dichromate was titrated against 1 N ferrous sulfate.

Total N in the soil was determined by the A.O.A.C. (3) Kjeldahl method, modified by adding salicylic acid during the digestion to include nitrate-N in the determination. Ammonia was distilled into a 4% boric acid solution with a mixed indicator of bromocresol green and methyl red, and titrated with 0.1 N hydrochloric acid solution.

Nitrogen in plant material was determined by a modified micro-Kjeldahl method described by Volk-Fontein.[1]

Organic P in the soil was determined by the ignition method as described by Olsen and Dean (56). This method entailed the extraction with concentrated hydrochloric acid of comparable soil samples before and after ignition. The difference in the inorganic P content of these extracts was taken as the organic phosphorus content of the soil.

Phosphorus was extracted from the soil by the Bray and Kurtz method (15). Phosphorus in the soil extract was determined by the stannous chloride and chloromolybdate procedure given by Truog (75). The transmittancy was measured in the Fisher colorimeter equipped with a red-glass filter.

The pH of the soil was determined in 2:1, water to soil suspension after 12 hours with a thin glass electrode and a Beckman Zeromatic pH meter. Enough solid potassium chloride was added to the suspension in water to make a 1 N salt solution. The pH was determined again after 30 minutes.

Ten grams of soil were extracted with 1 N ammonium acetate according to the method by Peech, et al. (60). The solution was evaporated to dryness, and the organic matter was oxidized with 6 N nitric acid solution and 30% hydrogen peroxide and evaporated to dryness.

The salts were taken up and diluted to 100 ml in 0.1 N hydrochloric acid.

Determinations of K and Na in the soil extracts were made with a Beckman B Flame Spectrophotometer with an acetylene-oxygen burner assembly at wavelengths of 770 and 589 mu respectively; the Ca and Mg concentrations in these extracts, were determined with a 303 Perkin-Elmer Atomic Absorption Spectrophotometer at wavelengths of 422.7 and 285.2 mu, respectively.

---

[1] Unpublished mimeographed sheet. Department of Soils, University of Florida, Gainesville, Florida.

One gram of plant material was wet digested by the method described by Ulrich, et al. (76). Samples were predigested with a concentrated nitric acid and finally digested with a tertiary acid mixture of 10 volumes of concentrated nitric acid, one volume of concentrated sulfuric acid and four volumes of a 60% perchloric acid until all of the perchloric acid had been volatilized leaving only a salt residue in the small volume of sulfuric acid. The final residue was taken up and diluted to 100 ml in water. One milliliter of this solution was taken for P determination by the stannous chloride and chloromolybdate procedure given by Truog (75). The transmittancy was measured in the Fisher colorimeter equipped with a red-glass filter.

Statistical Analysis

The data from each of the four experiments were analyzed statistically by the method outlined by LeClerg, et al. (46).

RESULTS AND DISCUSSION

Preliminary Experiment

This experiment was carried out at Zamorano with soils from sites A and B. The soils under study show the morphological characteristics of Vertisols, but the exchange capacity is less than 30 meq/100 g of soil as required by the Soil Survey Staff (72). Dudal (27) includes similar soils under the name of dark clay soils of tropical and sub-tropical regions. Profile descriptions, physical and chemical properties of these soils are given in Appendix Tables 16, 17 and 18, respectively. The study of these tables reveals that the top 40 to 50 cm layer of these soils is low in total N and extractable P, is relatively high in organic C and has high C/N and C/P ratios. Sorghum was used as the indicator plant. The yields of dry sorghum forage obtained in response to the applied treatments are shown in Table 1. The statistical analysis of these data indicated that the NP interaction was significant at the 5% level (Appendix Table 19). In this experiment interaction means the effect of N as conditioned by the presence of P. It also means that the effects of N and P are not additive. Snedecor (71) indicated that in the presence of interaction, it is rarely useful to ask about the main effect of the factors involved.

The totals for soils can be combined for a study of the significant NP interaction because no evident effect of soil either in the main effect or interaction was shown by the statistical analysis. The combined totals are given in the last column of Table 1. These values,

Table 1 - Yield of dry sorghum forage as influenced by N and P fertilization of two Zamorano soils

Fertilizer applied		Soils	Replications			Total	Combined total
N	P		1	2	3		
kg/ha			g/pot			g	g
0	0	A	1.6	1.4	1.0	4.0	
0	0	B	0.7	0.5	1.1	2.3	6.3
0	80	A	3.2	11.6	1.9	16.7	
0	80	B	4.4	2.5	2.5	9.4	26.1
200	0	A	0.1	1.1	0.6	1.8	
200	0	B	0.1	0.2	0.6	0.9	2.7
200	80	A	15.0	7.6	9.2	31.8	
200	80	B	20.4	9.1	8.8	38.3	70.1

calculated on per pot basis, are rearranged in Table 2. In this table the effects of N with and without P on yield of dry sorghum are shown. The difference in yields between the high and low level of N in the absence of P was -0.6 g/pot; this was a depressing effect on the yield of dry matter due to N application. However, the yield difference between the high and low level of N when P was added along with N was 7.3 g/pot. This means that N application increased the yield of sorghum in the presence of added P. The difference between 7.3 and -0.6 g/pot was 7.9 g/pot and measured the interaction between N and P. Therefore, it can be stated that in this experiment there was no single effect of N; instead there were two separate effects, one without P and another with P. It is also evident that there was no single effect of P; therefore, the main effect lost its meaning and more attention could be given to the interaction.

From Fig. 3, it is evident that applications of P alone increased yields from 1.3 to 5.6 g or dry matter/pot in the case of soil A and from 0.8 to 3.1 in the case of soil B.

In the presence of N, the yields obtained due to P applications increased from 0.6 to 10.6 g of dry matter/pot for soil B.

To study this interaction, several additional experiments were conducted.

Greenhouse Experiment With Millet

Dry matter

The yields of dry matter obtained on soils A and B as a response to the different treatments are shown in Table 3.

Table 2 - The effect of N and P applications on the yield of dry sorghum[a]

Applied P	Applied N kg/ha 0	 200	Difference
kg/ha	----------------	g/pot	--------------
0	1.1	0.5	-0.6
80	4.4	11.7	7.3**
Difference	3.3	11.2**	7.9*

[a] Average of 3 values and 2 soils.

*Significant at the 5% level.

**Significant at the 1% level.

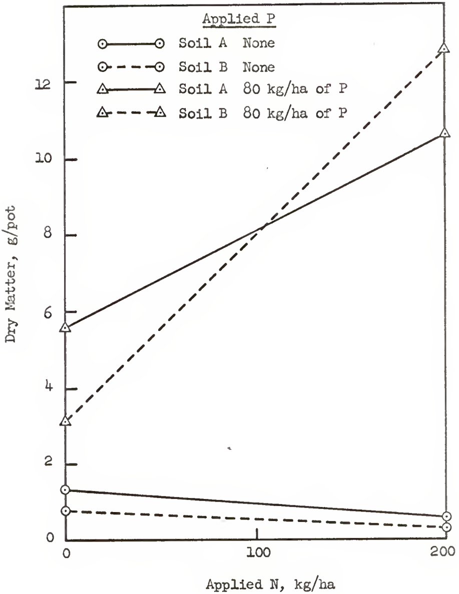

Fig. 3 - Yields of dry sorghum forage, as influenced by N and P applications.

Table 3 - Dry weight yield of millet plants as influenced by N, P and K fertilization of two Zamorano soils

Fertilizer applied				Replications			Total	Combined total
N	P	K	Soils	1	2	3		
	kg/ha				g/pot		g	g
0	0	0	A	8.6	8.6	8.7	25.9	
0	0	0	B	11.8	7.9	4.3	24.0	49.9
0	0	80	A	2.6	5.6	4.3	12.5	
0	0	80	B	5.9	6.7	5.7	18.3	30.8
0	200	0	A	22.9	26.9	25.9	75.7	
0	200	0	B	27.6	25.5	25.4	78.5	154.2
0	200	80	A	25.3	26.3	31.8	83.4	
0	200	80	B	23.9	30.2	26.7	80.8	164.2
100	0	0	A	2.8	3.6	3.3	9.7	
100	0	0	B	4.3	5.7	2.2	12.2	21.9
100	0	80	A	3.3	2.9	4.1	10.3	
100	0	80	B	2.7	4.8	3.2	10.7	21.0
100	200	0	A	27.5	29.9	27.5	84.9	
100	200	0	B	23.8	32.0	23.9	79.7	164.6
100	200	80	A	28.2	25.0	27.9	81.1	
100	200	80	B	25.0	28.0	26.4	79.4	160.5

The statistical analysis of the data showed that the NP interaction was highly significant and that the NPK interaction was significant at the 5% level (Appendix Table 20). No evident effect of the soils either in the main effect or interaction was detected. This warranted the combination of the totals for soils A and B. These combined totals are given in the last column of Table 3.

Because there was an effect of K in the significant NPK interaction, the combined totals of Table 3, calculated on per pot basis, were grouped according to amount of K added to the soil (Table 4).

The effect of N on the yield of millet plants in soils not treated with K was -4.6 g/pot in the absence of P and 1.7 g/pot in the presence of P. The difference between 1.7 and -4.6 g/pot was -6.3 g/pot and represented a measure of the NP interaction. In the presence of added K, the effect of N in the presence and absence of added P were -1.6 and -0.5 g/pot the NP interaction in this case was 1.1 g/pot.

The third degree interaction NPK was measured by the difference between 1.1 and -6.3 g/pot.

It is evident from the data of Table 4 that the NP interaction was more pronounced when K was not added to the soil.

The NP interaction in the absence of added K, that is, the effect of N as conditioned by the addition of P, is shown in Fig. 4. The yield increase due to N in the presence of P was greater than that due to N in the absence of P. When N alone was added, a decrease in yields was observed. However, the application of N and P together resulted in a yield increase.

Table 4 - The effect of N, P, and K applications on the yield of millet plants[a]

Applied P	Applied K	Applied N kg/ha 0	Applied N kg/ha 100	Difference for added N
kg/ha		g/pot		
		Without K		
0	0	8.3	3.7	-4.6*
200	0	25.7	27.4	1.7
Difference		17.4**	23.7**	-6.3**
		With K		
0	80	5.1	3.5	-1.6
200	80	27.3	26.8	-0.5
Difference		22.2**	23.3**	1.1**

[a] Average of 2 values and 2 soils.

* Significant at the 5% level.

** Significant at the 1% level.

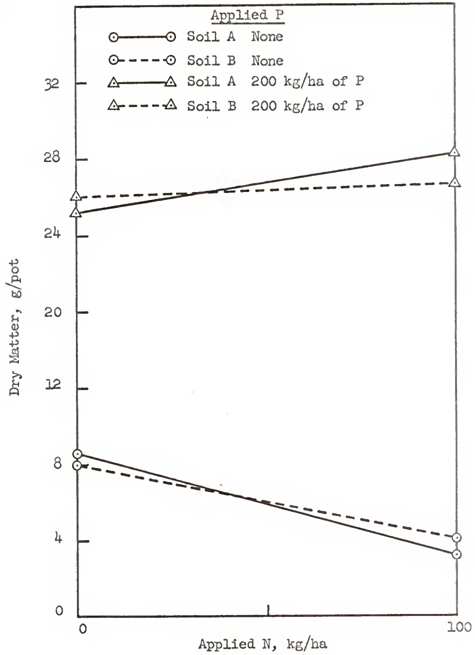

Fig. 4 - Yields of dry millet plants, as influenced by N and P applications.

Nitrogen uptake

The total uptake of N by millet as affected by the treatments is given in Table 5. The last column of this table is the combined total of the two levels of K for each treatment combination. This was done because no K effect was evident either in the main effect or interaction. Each combined total divided by six was entered in Table 6 to study the highly significant NP interaction (Appendix Table 21).

The study of Table 6 shows that the N uptake by millet on soil A increased by 3.4 mg/pot due to the addition of N. However, the N uptake increased by 77.5 mg/pot when N and P were added together. The difference between these two effects, 74.1 mg/pot, measured the NP interaction for soil A. For soil B, the interaction between N and P was found to be 77.5 mg/pot. The difference between the interaction in soil A and B was not significant. This indicates that the NP interaction in both soils was very much the same.

The N uptake from soil B was in every case higher than that from soil A. For instance, the N uptake for untreated soil A was 136.7 mg/pot, while for untreated soil B the N uptake was 164.5 mg/pot. The difference in N uptake due to soil was highly significant. The N uptake was influenced more strongly by the addition of P than by the addition of N. This indicates that in the soils under study P was more limiting than N.

The average total uptake of N by millet for four treatments is shown in Fig. 5. The interaction between N and P is illustrated. Additions of N alone to both soils decreased the N uptake by plants. However, additions of N plus P resulted in an increase of N uptake by

Table 5 - Uptake of N by millet as influenced by N, P and K fertilization of two Zamorano soils

Fertilizer applied				Replications			Total	Combined total
N	P	K	Soils	1	2	3		
	kg/ha			N uptake, mg/pot			mg	mg
0	0	0	A	139.2	149.7	144.8	433.7	820.4
0	0	80	A	116.3	139.0	131.4	386.7	
0	200	0	A	170.9	165.0	180.0	515.9	1,033.3
0	200	80	A	168.6	183.1	165.7	517.4	
100	0	0	A	127.2	143.6	131.8	402.6	841.1
100	0	80	A	142.0	128.2	168.3	438.5	
100	200	0	A	237.8	290.8	235.7	764.3	1,501.0
100	200	80	A	239.2	244.6	252.9	736.7	
0	0	0	B	226.6	164.4	132.8	523.8	987.2
0	0	80	B	142.7	161.8	158.9	463.4	
0	200	0	B	206.4	204.2	214.0	624.6	1,260.3
0	200	80	B	205.5	231.1	199.1	635.7	
100	0	0	B	171.1	213.7	105.3	490.1	923.4
100	0	80	B	129.3	176.9	127.1	433.3	
100	200	0	B	265.9	310.9	283.8	860.6	1,661.3
100	200	80	B	264.7	297.9	238.1	800.7	

Table 6 - The effect of N and P applications on the uptake of N by millet[a]

Applied P	Applied N kg/ha 0	200	Difference
kg/ha	N uptake, mg/pot		
	Soil A		
0	136.8	140.2	3.4
200	172.6	250.2	77.6**
Difference	35.8*	110.0**	74.2**
	Soil B		
0	164.5	153.9	-10.6
200	210.0	276.9	66.9**
Difference	45.5*	123.0**	77.5**

[a] Average of 3 values and 2 levels of K.

*Significant at the 5% level.

**Significant at the 1% level.

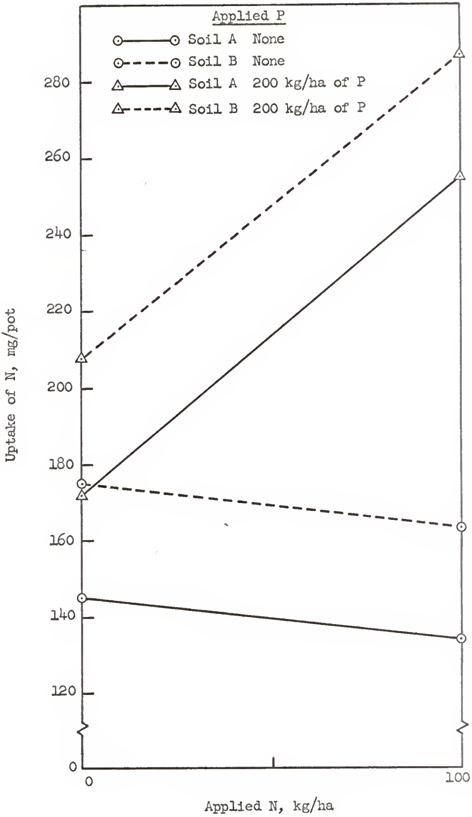

Fig. 5 - Uptake of N by millet, as influenced by N and P applications.

millet. Where only P was applied, N uptake increased, but this increase was significantly greater when N was added together with P.

Phosphorus uptake

Total P uptake by millet for the treatments are shown in Table 7. Statistical analysis of these data showed that the uptake of P responded to the amount of P applied and to the soils. Because the soil and P effects were found to be significant and highly significant, respectively, the data of Table 7 were summarized and entered in Table 8 for study. For both soils A and B, the addition of N alone decreased the uptake of P by millet. These effects were -1.3 and -1.7 mg of P/pot and were not statistically significant. However, they suggested the possibility of a drop in available P for the plants caused by the application of N. When N and P were added together, the phenomenon mentioned above did not occur.

In both soils A and B, the addition of P enhanced the P uptake by plants equally in the presence or absence of added N. In other words, no significant NP interaction was evident.

Soil B provided the plants with more P than soil A. For example, the uptake of P from untreated soil B was 0.7 mg/pot higher than that of untreated soil A. In every case the P uptake by millet from soil B exceeded that from soil A. This indicated that soil B had a significantly higher content of available P than soil A.

The absence of NP interaction is illustrated by Fig. 6. The average total uptake of P by millet for eight treatments is shown in this figure. As pictured in the graph, P uptake was significantly affected only by the addition of P fertilizer to the soil.

Table 7 - Uptake of P by millet as influenced by N, P, and K fertilization of two Zamorano soils

Fertilizer applied				Replications			Total	Combined total
N	P	K	Soils	1	2	3		
	kg/ha			P uptake, mg/pot			mg	mg
0	0	0	A	4.3	4.0	3.1	11.4	
0	0	80	A	1.2	2.5	1.7	5.4	16.8
0	200	0	A	68.7	78.0	72.3	219.0	
0	200	80	A	80.1	79.8	65.2	225.1	444.1
100	0	0	A	1.3	1.6	1.7	4.6	
100	0	80	A	1.5	1.2	1.6	4.3	8.9
100	200	0	A	71.6	81.5	71.8	224.9	
100	200	80	A	75.0	71.3	82.4	228.7	453.6
0	0	0	B	5.6	3.1	2.3	11.0	
0	0	80	B	3.2	3.4	3.2	9.8	20.8
0	200	0	B	78.7	73.4	77.3	229.4	
0	200	80	B	80.1	79.8	65.2	225.1	454.5
100	0	0	B	2.5	2.3	1.1	5.9	
100	0	80	B	1.0	2.5	1.6	5.1	11.0
100	200	0	B	79.0	85.0	73.7	237.7	
100	200	80	B	70.2	84.1	87.5	241.8	479.5

Table 8 - The effect of N and P applications on the uptake of P by millet[a]

Applied P	Applied N kg/ha 0	Applied N kg/ha 100	Difference
kg/ha	P uptake, mg/pot		
	Soil A		
0	2.8	1.5	-1.3
200	74.0	75.6	1.6
Difference	71.2**	74.1**	2.9
	Soil B		
0	3.5	1.8	-1.7
200	75.8	79.9	4.1
Difference	72.3**	78.1**	5.8

[a] Average of 3 values and 2 levels of K.

** Significant at the 1% level.

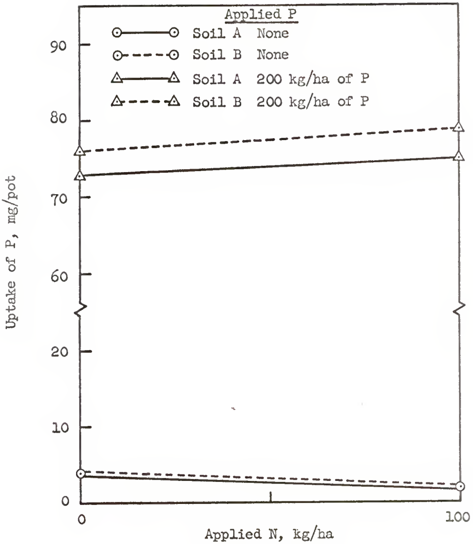

Fig. 6 - Uptake of P by millet, as influenced by N and P applications.

Organic and inorganic phosphorus content of the soil

The organic and inorganic P contents of the soil were measured at the end of the experiment. The results of organic P for each treatment are given in Table 9. Because of the significant NPK interaction, (Appendix Table 23) data in Table 9 were entered in Table 10 for study. Addition of N to soil A in the absence of K increased the organic P level of the soil. The organic P increased by 14 ppm due to the addition of N (Table 10). The same increase was obtained for the N treatment of soil A with K. However, when N and P were added together, the organic P decreased by 26 ppm. This means that the effect of N and P, when added together, was significantly modified by the addition of K.

In soil B the organic P increased with the addition of N and P. However, the treatment consisting of N alone failed to increase the soil organic P. The reason for this departure from the trend found for soil A was not determined from the data available on this soil.

The addition of K increased the organic P on the N treated soil by 22 ppm. However, this increase was only 2 ppm when N and P were added together. This indicated that there are two different effect of K, one in the absence of P and another in the presence of P.

From Table 10, it is evident that with the exception of the NPK treatment of soil A and the K treatment of soil B, the soil organic P increased due to the application of N. The effects of N and P fertilization on the soil organic P are shown in Fig. 7. Organic P in soil A increased significantly due to the addition of N. Similar increase was found in soil B except for the treatment consisting of N alone.

The results of the applied treatments on the inorganic P content

Table 9 - Organic P content in two soils from Zamorano as influenced by N, P, and K fertilization

Fertilizer applied				Replications			Total
N	P	K	Soils	1	2	3	
	kg/ha				P, ppm		
0	0	0	A	83	73	78	234
0	0	80	A	115	102	73	290
0	200	0	A	96	92	93	281
0	200	80	A	106	125	121	352
100	0	0	A	104	97	73	274
100	0	80	A	106	117	109	332
100	200	0	A	103	118	101	322
100	200	80	A	101	102	73	276
0	0	0	B	111	102	94	307
0	0	80	B	122	128	68	318
0	200	0	B	104	122	89	315
0	200	80	B	117	127	85	329
100	0	0	B	110	103	94	307
100	0	80	B	156	120	110	386
100	200	0	B	123	153	120	396
100	200	80	B	119	123	94	336

Table 10 - The effect of N, P, and K applications on the soil organic P content[a]

Applied P	Applied K	Applied N kg/ha 0	Applied N kg/ha 100	Difference
kg/ha		P, ppm		
		Soil A without K		
0	0	78	92	14
200	0	94	108	14
Difference		16	16	0
		Soil A with K		
0	80	96	110	14
200	80	118	92	-26*
Difference		22	-18	-40
		Soil B without K		
0	0	102	102	0
200	0	106	132	26*
Difference		4	30	26
		Soil B with K		
0	80	106	128	22
200	80	110	112	2
Difference		4	-16	-20

[a] Average of 3 values.
*Significant at the 5% level.

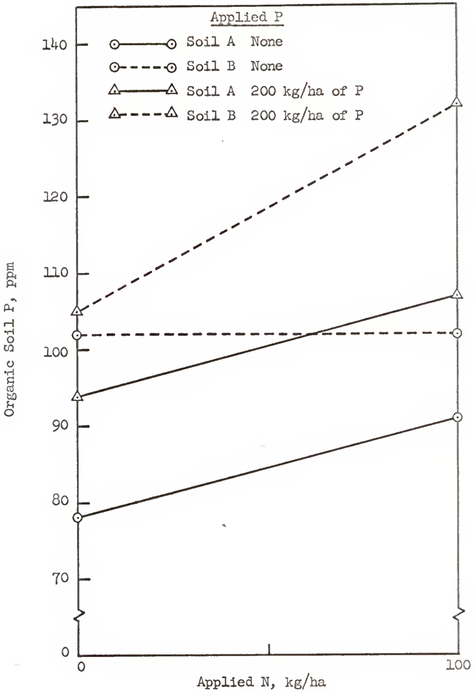

Fig. 7 - Changes in organic soil P, as influenced by N and P applications.

in the soil are given in Table 11. The effects of N, P, and K on soil organic P are given in Table 12. The study of this table revealed that in the absence of added P, the addition of N decreased the inorganic P of the soil. However, the effect of N was different in the presence of both P and K. For instance, in Soil A with K, the addition of N and P together, increased the soil inorganic P. The same effect was also observed in soil B treated with K.

The significant decrease in inorganic P as a result of N application is shown in Fig. 8.

The NP interaction as reflected by yields of dry matter of millet was due to the decrease of soil inorganic P caused by the application of N as shown in Table 12 and Fig. 8. This decrease of inorganic P was caused by corresponding conversion to organic P. It is shown in Table 10 and Fig. 7 that organic P increased due to N application. Upon addition of N, soil microbes which have high P demand for their metabolism can incorporate some of the inorganic P and metabolically convert this to organic P. The inorganic P converted to organic P included much of the available P. This is suggested by data in Table 8. These data showed that the uptake of P by millet plants was decreased by the addition of N alone. Therefore, the plants experienced a severe P deficiency which resulted in poor vegetative growth.

Thus, the NP interaction in both soils from Honduras was probably from microbial activity. The utilization of soil inorganic P by soil micro-organisms was well documented from previous work by Hardy and Hewitt (37), Swaby and Sherber (73), Roche (65), Sen, et al. (68), Das (22) and Rao, et al. (62).

Table 11 - Inorganic P content in two soils from Zamorano as influenced by N, P, and K fertilization

Fertilizer applied			Soils	Replications			Total
N	P	K		1	2	3	
	kg/ha				P, ppm		
0	0	0	A	49	52	47	148
0	0	80	A	42	39	39	120
0	200	0	A	89	96	100	285
0	200	80	A	78	70	70	218
100	0	0	A	38	44	47	129
100	0	80	A	26	31	26	83
100	200	0	A	77	88	94	259
100	200	80	A	78	89	83	250
0	0	0	B	68	70	63	201
0	0	80	B	52	63	80	195
0	200	0	B	104	110	115	329
0	200	80	B	94	83	109	286
100	0	0	B	59	70	62	191
100	0	80	B	54	52	62	168
100	200	0	B	96	110	109	315
100	200	80	B	98	96	102	296

Table 12 - The effect of N, P, and K applications on the soil inorganic P[a]

Applied P	Applied K	Applied N kg/ha 0	Applied N kg/ha 100	Difference
kg/ha		P, ppm		
		Soil A without K		
0	0	50	44	- 6**
200	0	96	86	-10**
Difference		46**	42**	- 4**
		Soil A with K		
0	80	40	28	-12**
200	80	72	84	12**
Difference		32**	56**	24**
		Soil B without K		
0	0	68	64	- 4*
200	0	110	106	- 4*
Difference		38*	38*	0
		Soil B with K		
0	80	66	56	-10**
200	80	96	98	2
Difference		30*	42*	12**

[a] Average of 3 values.

*Significant at the 5% level.

**Significant at the 1% level.

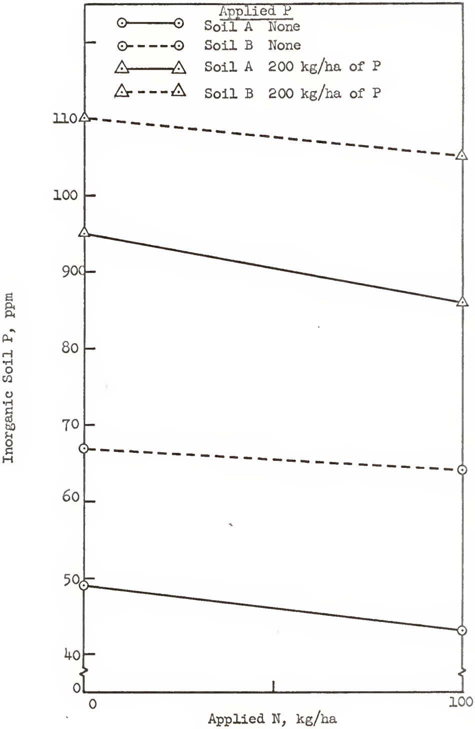

Fig. 8 - Changes in inorganic soil P, as influenced by N and P applications.

Carbon Dioxide Evolution Experiment

This experiment was designed to provide more information on the conversion of soil inorganic P to organic P.

It was assumed that the activity of the microbial population that had become reestablished after methyl bromide fumigation was not significantly different from that of the pretreated soil.

Effect of nitrogen application on soil organic phosphorus and carbon dioxide production

The level of organic P as related to each N application is indicated in Fig. 9a and Table 13. There were no significant differences in soil organic P content due to treatments.

The average CO_2 production decreased significantly in response to N application. From the data it may be inferred that N applications at these rates did not enhance microbial activity in the soil under study.

Effect of phosphorus application on soil organic phosphorus and carbon dioxide production

Significant differences in soil organic P were not found at the rates of P applied (Fig. 9a).

Production of CO_2 increased significantly with addition of P (Table 13). This indicated that P deficiency was the factor which limited organic P mineralization in the soil.

Organic matter mineralization was not enhanced by applied N in the absence of suitable amounts of P (Table 13 and Fig. 9a). For example, the average CO_2-C production for the check and where the N applied was at the rate of 100 kg/ha was 72.30 and 74.50 mg, respectively.

Table 13 - The mean effect of N and P applications on CO_2 production and organic P content of a soil from Zamorano

Fertilizer applied		CO_2 evolved*	Soil organic P
N	P		
kg/ha		CO_2-C, mg/200 g of soil	P, ppm
100	240	79.22 a	67.8
0	80	78.61 ab	81.2
200	80	75.40 b	75.0
100	80	74.71 c	92.5
100	0	74.50 c	77.5
0	0	72.30 c	85.0

*Values not followed by the same letter are significantly different at the 5% level.

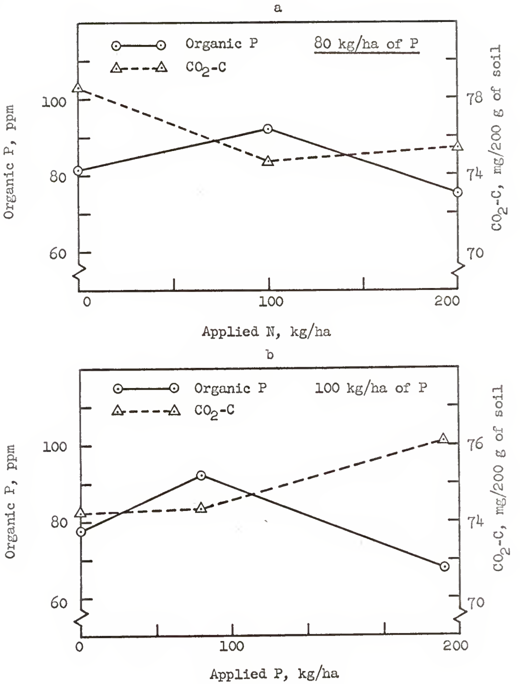

Fig. 9 - The effect of N and P applications on soil organic P and production of CO$_2$.

The difference between these two values was not statistically significant. However, the difference between the check and the P treatment was significant at the 5% level (Table 13).

Although the changes of soil organic P caused by P application in the presence of N were not significant, there was an indication of an increase in the soil organic P where fertilizer P was applied at the rate of 80 kg/ha (Fig. 9b). This increase was not observed where P was applied at 240 kg/ha. Sengupta and Cornfield (69) indicated that at higher levels of soluble P in the soil, mineralized P is not reassimilated by the micro-organisms to the same extent as at lower P levels. When high P availability exists, the mineralization of organic P is increased and results in a decrease in soil organic P. Conversely, at low P availability, mineralized P and available P are converted to organic P by microbial metabolism.

Effects of Rate and Placement of Fertilizer Phosphorus on Dry Matter Yield and Nutrient Uptake of Oats Grown on Soil A

Data discussed in previous sections showed that N and P applications to the soils under study were necessary to obtain maximum millet yields.

This experiment was designed to test the effect of several rates and placement patterns of P application on yield and nutrient uptake of oats grown on Zamorano soil A. The applied N was fully incorporated at the rate of 100 kg/ha uniformly for each P treatment.

The P uptake by oats from banded and fully incorporated P application was compared with theoretical considerations proposed by DeWit (24).

The detailed data for this experiment are given in Appendix Tables 29 and 30. The mean yield of dry matter and mean P uptake for each treatment are shown in Table 14.

Statistical analyses of the P uptake are shown in Table 14 and Appendix Table 31. These indicated that highly significant differences existed among treatments.

The relationships between yield of dry matter, P uptake, and rate of P fertilization are presented in Fig. 10. The P response as indicated by the yield of dry matter is obvious from the graph. Yields of dry matter for the P applied at 40, 120 and 240 kg/ha treatments were almost triple the yield obtained without P addition. Rates of P application higher than 40 kg/ha did not result in higher yields. However, the P uptake by oats increased with increasing rates of P application (Fig. 10).

Theoretical evaluation of phosphorus placement

The compensation function of DeWit (24) was used since the concentration of fertilizer in the banded and fully incorporated patterns were the same. DeWit (24) also indicated that the compensation function was valid only when a relatively small part of the fertilizer (less than 30%) was recovered by the plants. He derived a correction factor for the high recovery percentage effects on the Ur/Ub value. Ur represented the uptake from the banded fertilizer and Ub represented uptake from the fully incorporated fertilizer.

In the present study, four treatments given in Table 14 qualified as conditions applicable to the compensation function. For these treatments, the P recoveries in plant tissue were 44, 49, 36 and 25%, respectively. Therefore, consideration was given to relatively high

Table 14 - The effect of P application on yield and P uptake of oats grown in the greenhouse on a soil from Zamorano

Treatment	Soil volume	Mean yield	Mean* P uptake
P, kg/ha		Dry tissue, g/pot	P, mg/pot
0	Entire	3.7	2.69 a
40	Top 1/3	12.3	18.96 b
40	Entire	11.2	19.95 b
120	Entire	10.6	35.98 c
120	Top 1/2	13.8	40.98 c
240	Entire	12.2	57.20 d

[*] Values not followed by the same letter are significantly different at the 5% level.

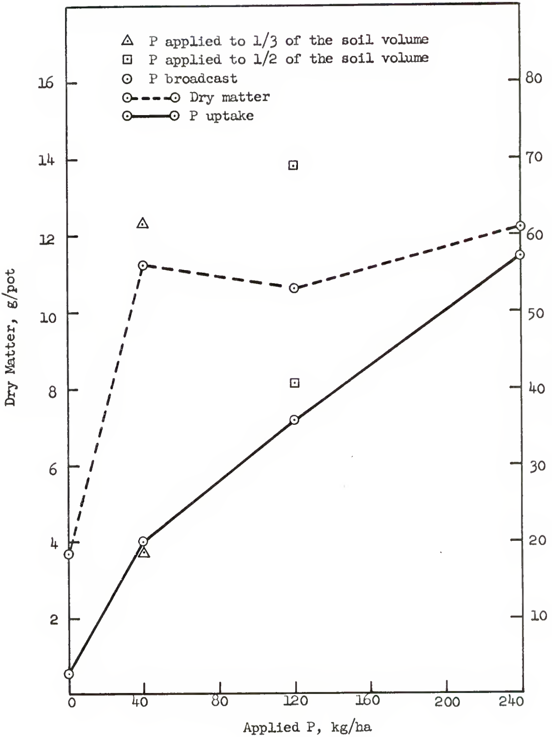

Fig. 10 - Yields of dry matter and P uptake by oats, as influenced by placement and rate of P application.

recovery percentages of P in calculating the Ur/Ub values.

The Ur/Ub values predicted from the compensation function were 0.62 and 0.74 where Xr/Xb values were 0.33 and 0.50, respectively. The fraction of the soil volume in the pot to which fertilizer was applied was represented by Xr and the volume of the soil in the pot by Xb.

The observed and calculated Ur/Ub values for the four treatments mentioned above are given in Table 15. The calculated Ur/Ub values were obtained using the modification proposed by Hammond and Robertson (32). Their equation was a rearrangement of DeWit's original equation which corrected for the effect of high recovery on the Ur/Ub value. The observed Ur/Ub values (Table 15) were lower than those predicted from the compensation function. However, when adjustment was made for the relatively high P recovery, the observed value followed the compensation function.

Hammond and Robertson (32) indicated that, experimentally, Ur/Ub values lower than those obtained from the compensation function suggest little advantage of banded over fully incorporated application. Since this was the case for the soil under study, there was no advantage of banded over fully incorporated application of P fertilizer. In this soil, P availability from fertilizer resulted in relatively high recovery of P. Although P uptake increased with the rate of P fertilization, the differences between P uptake from the banded and fully incorporated application were not statistically significant (Table 14 and Fig. 10).

Table 15 - Phosphorus uptake ratios in relation to fertilizer placement ratios[a]

Treatment comparison	Xr/Xb	Ur/Ub	
		Observed	Calculated[b]
P, kg/ha			
40 in top 1/3 compared with 120 in entire soil	0.33	0.49	0.48
120 in top 1/2 compared with 240 in entire soil	0.50	0.70	0.66

[a] Symbols:

Xr is the fraction of the soil volume in the pot to which fertilizer was applied; Xb is the soil volume in the pot; Ur is the uptake from locally applied fertilizer; and Ub is uptake from the broadcast application.

[b] Derived from equation 2 by Hammond and Robertson (32).

SUMMARY AND CONCLUSIONS

Greenhouse and laboratory experiments were conducted on two soils from Zamorano which had been under different management practices and had received no fertilizer during the past 20 years. Studies included the effects and interactions of N and P on yields of dry matter, nutrient uptake, and organic and inorganic fractions of soil P.

Soil profile descriptions were made at two sites, A and B. One site was located within the boundaries of the Escuela Agricola Panamericana and the other on a neighboring farm.

Surface soil samples to a depth of 15 cm were collected from both sites for greenhouse and laboratory studies. Samples of each horizon were taken for chemical and physical analyses. Undisturbed soil cores were obtained for bulk density determinations.

The soils used in the study were low in total N and available P content. They were found to have a high C/P ratio and approximately 60% of their total P was in the organic fraction.

Morphologically the soils under investigation could be classified as Vertisols except that the exchange capacities were lower than that stipulated for Vertisols.

The effect of N on yields of dry sorghum forage was negative in the absence of added P and positive in the presence of added P. This interaction, that is, the effect of N as conditioned by the addition of P, was highly significant. This pot test experiment was conducted at Zamorano, Honduras.

Yields of dry millet tissue obtained from an experiment conducted at the University of Florida also indicated a similar highly significant NP interaction. This interaction was also found for N uptake by millet plants. The NP interaction for P uptake was not detected. The effects of soil and applied P on the uptake of P by plants were significant and highly significant, respectively.

The P fractionation data showed that N application increased the organic P content and decreased the inorganic P content of the soil. It was also observed that millet plants grown on soil treated only with N had a lower P content than plants grown on non-treated soil.

The activity of micro-organisms, as measured by CO_2 production, decreased significantly in response to N application. However, addition of P significantly increased the CO_2 production. Significant differences in soil organic P were not found as a result of N or P applications although there was a slight increase of organic P where P was applied at 80 kg/ha.

Observed P recoveries due to placement were lower than those predicted from DeWit's theory. However, when the high percent recovery of P was considered, the observed and theoretical values were in close agreement.

The uptake of P from broadcast and localized application as P at 40 kg/ha was not statistically significant. This was also true where the P rate was 120 kg/ha.

The following conclusions were made:

1. Response to N applications was not obtained until a sufficient supply of available P was assured.

2. Available P in the soil decreased with N application.
3. The decrease of inorganic P and the increase of organic P were due to microbial action.
4. Soil microbial activity, as evidenced by CO_2 evolution, was lower where P was not applied than where P was applied.
5. Mineralization of organic P by soil micro-organisms was increased when sufficient soluble P was applied to the soil.
6. Unavailability of P to plants was the major factor which limited plant growth.
7. No advantage was found of localized over broadcast application of fertilizer P.

APPENDIX

Table 16 - Profile descriptions of two Zamorano soils

Depth	Morphology
Soil A at pit 1	
0-15 cm	Dark brown (10YR 2/3) clay loam; strong angular blocky structure; very hard, friable, plastic, and sticky, gradual boundary; pH in H_2O, 6.3; pH in N KCl, 5.1.
15-45 cm	Very dark brown (10YR 2/2) clay loam; strong angular blocky structure; very hard, friable, plastic, and sticky; gradual boundary; pH in H_2O, 6.2; pH in N KCl, 4.5.
45-67.5 cm	Very dark grayish-brown (10YR 3/2) clay loam; moderate granular structure; very hard; firm, plastic, and sticky; gradual boundary; pH in H_2O, 6.3; pH in N KCl, 4.4.
67.5-82.5 cm	Dark brown (7.5YR 3/2) loam; medium angular blocky structure; very hard; firm, plastic and sticky, clear boundary; pH in H_2O, 6.3; pH in N KCl, 4.2; red and brown concretions.
82.5-100 cm	(2.5YR 3/4) sandy clay; angular blocky structure, very hard, firm, plastic sticky; pH in H_2O, 6.2; pH in N KCl, 4.2; red and brown concretions.
Soil A at pit 2	
0-37 cm	Very dark gray (10YR 3/1) sandy clay loam; strong angular blocky structure; very hard, friable, plastic and stidky; gradual boundary; pH in H_2O, 6.8; pH in N KCl, 5.2.
37-75 cm	Dark yellowish-brown (10YR 3/4) sandy clay loam; moderate granular structure; very hard; friable, plastic and sticky; gradual boundary; pH in H_2O, 6.6; pH in N KCl, 4.9.
75-105 cm	Dark yellowish-brown (10YR 3/4) clay loam; moderate granular structure, very hard, firm, very plastic and very sticky, pH in H_2O, 6.2; pH in N KCl, 4.5.

Table 16 -- Continued

Depth	Morphology
Soil B at pit 1	
0-45 cm	Very dark brown (10YR 2/2) sandy clay loam; moderate angular blocky structure, very hard, friable, plastic, and sticky; gradual boundary; pH in H_2O, 6.4; pH in N KCl, 5.1.
45-75 cm	Very dark brown (10YR 2/2) sandy clay loam; moderate angular blocky structure, very hard, friable, plastic and sticky; pH in H_2O, 6.6; pH in N KCl, 4.9.
Soil B at pit 2	
0-63 cm	Very dark brown (10YR 2/2) clay loam; moderate angular blocky structure; very hard, friable, plastic, and sticky; gradual boundary; pH in H_2O, 5.7; pH in N KCl, 4.7.
63-87 cm	Dark yellowish brown (10YR 3/4) clay loam; moderate angular blocky structure, very hard, friable, plastic, and sticky, gradual boundary; pH in H_2O, 5.9; pH in N KCl, 4.7.
87-150 cm	Pale brown (10YR 6/3) clay loam; moderate angular blocky structure, very hard, friable, plastic, and sticky; pH in H_2O, 6.2; pH in N KCl, 5.1.

Table 17 - Physical properties of soils

Depth	Particle density	Sticky point	Sand	Index of texture	Bulk density	Porosity Total	Porosity Capillary	Porosity Non-capillary
cm	g/cm^3	-----------	%	-----------	g/cm^3	--------------	%	--------------
				Soil A				
0-15	2.27	38.0	36	30.8	1.05	53	32	21
15-45	2.27	29.0	27	23.6	1.05	53	25	28
45-67	2.57	20.3	41	12.1	1.52	41	18	23
67-82	2.57	14.5	46	5.3	1.44	43	8	35
82-100	2.57	18.9	48	9.3	1.44	43	13	30
0-37	2.27	32.9	56	21.7	1.26	45	27	18
37-75	2.57	23.8	59	12.0	1.56	39	19	20
75-100	2.57	16.7	55	5.7	1.34	48	8	40
				Soil B				
0-45	2.27	41.7	55	30.7	1.12	51	34	17
45-75	2.57	24.1	58	12.5	1.19	54	15	39
0-63	2.27	28.4	42	20.0	1.13	50	23	27
63-87	2.57	27.5	42	19.1	1.18	59	23	36
87-150	2.57	27.5	43	18.9	1.07	58	20	38

Table 18 - Chemical properties of soils

Depth	Total N	Organic C	P[a]	Exchangeable cations				Ratios				
				Ca	Mg	K	Na	$\frac{C}{N}$	$\frac{C}{P^b}$	$\frac{Ca}{Mg}$	$\frac{Mg}{K}$	$\frac{Ca + Mg}{K}$
cm	%		ppm	meq/100 g								
				Soil A								
0-40	0.16	2.32	1.9	8.4	2.5	0.6	0.3	14.1	297	3.4	4.0	17.7
40-72	0.05	0.52	0.5	4.2	1.2	0.5	0.3			3.4	2.4	11.4
72-102	0.04	0.29	0.4	4.0	1.4	0.5	0.3			3.0	2.9	10.6
				Soil B								
0-52	0.20	3.14	1.8	9.8	2.8	0.5	0.3	15.4	320	3.5	5.4	24.4
52-80	0.06	0.98	0.6	7.1	2.3	0.9	0.3			3.5	2.2	9.9
80-150	0.05	0.70	0.6	5.4	2.5	0.9	0.3			2.2	2.7	8.4

---

[a] Phosphorus extracted from 5 g of air-dried soil with 35 ml of 0.03 N NH_4F in 0.1 N HCl as described by Bray and Kurtz (15).

[b] Organic P determined by the difference in P extractable with 12 N HCl before and after ignition as described by Olsen and Dean (56).

Table 19 - Analysis of variance for yield of dry sorghum forage obtained in response to N and P fertilization of two Zamorano soils

Source		Degrees of freedom	Mean squares	F
Replications		2	12.36	
Treatments:		7	70.85	
Nitrogen,	N	1	68.00	6.26*
Phosphorus,	P	1	316.83	29.20**
	NP	1	94.41	8.70*
Soil,	S	1	0.48	0.04
	SN	1	8.88	0.81
	SP	1	0.13	0.01
	SNP	1	7.04	0.65
Error		14	10.85	

*Significant at the 5% level.

**Significant at the 1% level.

Table 20 - Analysis of variance for dry weight yield of millet plants obtained in response to N, P, and K fertilization of two Zamorano soils

Source		Degrees of freedom	Mean squares	F
Replications		2	9.5	
Treatments:		15	383.2	
Soil,	S	1	0.00	0.00
Nitrogen,	N	1	20.01	4.32*
	SN	1	1.37	0.29
Phosphorus,	P	1	5,631.12	1,216.22**
	SP	1	3.79	0.82
	NP	1	41.30	8.92**
	SNP	1	0.77	0.17
Potassium,	K	1	4.14	0.89
	SK	1	0.28	0.06
	NK	1	0.35	0.07
	SNK	1	0.17	0.04
	PK	1	13.97	3.01
	SPK	1	1.17	0.25
	NPK	1	21.73	4.69*
	SNPK	1	7.28	1.57
Error		30	4.63	

*Significant at the 5% level .

**Significant at the 1% level.

Table 21 - Analysis of variance for N uptake by millet grown on two Zamorano soils fertilized with N, P, and K

Source		Degrees of freedom	Mean squares	F
Replications		2	1,900.23	
Treatments:		15	7,816.13	
Soil,	S	1	8,442.64	16.24**
Nitrogen,	N	1	14,195.85	27.31**
	SN	1	473.07	0.91
Phosphorus,	P	1	73,924.24	142.23**
	SP	1	398.07	0.76
	NP	1	17,330.66	33.34**
	SNP	1	6.59	0.01
Potassium,	K	1	859.11	1.65
	SK	1	345.56	0.68
	NK	1	3.65	0.007
	SNK	1	305.97	0.58
	PK	1	58.90	0.11
	SPK	1	144.10	0.27
	NPK	1	724.40	1.39
	SNPK	1	2.09	0.004
Error		30	519.74	

*Significant at the 5% level.

**Significant at the 1% level.

Table 22 - Analysis of variance for P uptake by millet grown on two Zamorano soils fertilized with N, P, and K

Source	Degrees of freedom	Mean squares	F
Replications	2	50.30	
Treatments:	15	4,490.63	
Soil, S	1	83.39	4.26*
Nitrogen, N	1	8.04	0.41
SN	1	1.08	0.05
Phosphorus, P	1	67,136.74	3,435.86**
SP	1	54.20	2.77
NP	1	1.15	0.05
SNP	1	0.27	0.01
Potassium, K	1	10.40	0.53
SK	1	4.81	0.24
NK	1	21.29	1.08
SNK	1	4.99	0.25
PK	1	31.44	1.61
SPK	1	0.88	0.04
NPK	1	0.20	0.01
SNPK	1	0.55	0.02
Error	30	19.54	

*Significant at the 5% level.

**Significant at the 1% level.

Table 23 - Analysis of variance for organic P content of two Zamorano soils fertilized with N, P, and K

Source		Degrees of freedom	Mean squares	F
Replications		2	2,079.44	
Treatments:		15	569.17	
Soil,	S	1	2,310.18	14.97**
Nitrogen,	N	1	858.52	5.56*
	SN	1	247.52	1.60
Phosphorus,	P	1	526.68	3.41
	SP	1	38.52	0.24
	NP	1	196.02	1.27
	SNP	1	11.02	0.07
Potassium,	K	1	697.68	4.52*
	SK	1	188.02	1.21
	NK	1	305.02	1.97
	SNK	1	247.52	1.60
	PK	1	1,054.68	6.80*
	SPK	1	46.02	0.29
	NPK	1	1,419.18	9.19**
	SNPK	1	391.02	2.53
Error		30	154.32	

*Significant at the 5% level.

**Significant at the 1% level.

Table 24 - Analysis of variance for inorganic P content of two Zamorano soils fertilized with N, P, and K

Source		Degrees of freedom	Mean squares	F
Replications		2	176.89	
Treatments:		15	1,873.66	
Soil,	S	1	4,981.68	1,203.30**
Nitrogen,	N	1	172.52	41.67**
	SN	1	1.68	0.40
Phosphorus,	P	1	20,958.52	5,062.40**
	SP	1	77.52	18.72**
	NP	1	188.02	45.41**
	SNP	1	17.52	4.23*
Potassium,	K	1	1,210.02	292.27**
	SK	1	72.52	17.51**
	NK	1	46.02	11.11**
	SNK	1	22.68	5.47*
	PK	1	25.52	6.16
	SPK	1	20.02	4.83*
	NPK	1	285.18	68.88**
	SPNK	1	25.52	4.83*
Error		30	4.14	

*Significant at the 5% level.

**Significant at the 1% level.

Table 25 - The effect of N and P applications on CO_2 production from a Zamorano soil

Fertilizer applied		Replications		Mean
N	P	1	2	
kg/ha		CO_2-C, mg/200 g of soil		
0	0	73.10	71.50	72.30
100	0	75.34	73.67	74.50
0	80	79.23	77.99	78.61
100	80	74.55	74.88	74.71
200	80	73.91	76.89	75.40
100	240	78.66	79.78	79.22

Table 26 - The effect of N and P applications on organic P content of a soil from Zamorano

Fertilizer applied		Replications		Mean
N	P	1	2	
kg/ha		Organic P, ppm		
0	0	87.5	82.5	85.0
100	0	75.0	80.0	77.5
0	80	75.0	87.5	81.2
100	80	90.0	95.0	92.5
200	80	60.0	90.0	75.0
100	240	62.8	77.8	67.8

Table 27 - Analysis of variance for CO_2 production in a Zamorano soil fertilized with N and P

Source	Degrees of freedom	Mean squares	F
Replications	1	0.00	
Treatments	5	13.94	8.13*
Error	5	1.71	

*Significant at the 5% level.

Table 28 - Analysis of variance for organic P content of a Zamorano soil treated with N and P

Source	Degrees of freedom	Mean squares	F
Replications	1	275.5	
Treatments	5	145.1	2.14
Error	5	68.2	

Table 29 - Dry weight yield of oat plants as influenced by P fertilization of a Zamorano soil

Treatment[a]	Soil volume	Replications		Mean
		1	2	
P, kg/ha			g/pot	
0	Entire	4.3	3.1	3.7
40	Entire	9.8	12.7	11.2
120	Entire	10.6	10.7	10.6
240	Entire	13.2	11.2	12.2
40	Top 1/3	12.5	12.1	12.3
120	Top 1/2	11.0	16.6	13.8

[a] Basal treatment of N is 100 kg/ha; of K is 200 kg/ha.

Table 30 - Uptake of P by oats as influenced by P fertilization of a Zamorano soil

Treatment[a]	Soil volume	Replications 1	Replications 2	Mean
P, kg/ha		P uptake, mg/pot		
0	Entire	3.33	2.06	2.69
40	Entire	16.04	23.87	19.95
120	Entire	34.18	37.79	35.98
240	Entire	60.89	53.52	57.20
40	Top 1/3	17.50	20.43	18.96
120	Top 1/2	35.09	46.87	40.98

[a] Basal treatment of N is 100 kg/ha; K is 200 kg/ha.

Table 31 - Analysis of variance for P uptake by oats grown on a Zamorano soil fertilized with N, P, and K

Source	Degrees of freedom	Mean squares	F
Replications	1	25.50	
Treatments	5	744.70	32.80**
Error	5	22.70	

**Significant at the 1% level.

LITERATURE CITED

1. Al-Abbas, A. H., and S. A. Barber. 1964. A soil test for phosphorus based upon fractionation of soil phosphorus: I. Correlation of soil phosphorus fractions with plant available phosphorus. Soil Sci. Soc. Amer. Proc. 28: 218-221.

2. Al-Abbas, A. H., and S. A. Barber. 1964. A soil test for phosphorus based upon fractionation of soil phosphorus: II. Development of the soil test. Soil Sci. Soc. Amer. Proc. 28: 222-224.

3. Association of Official Agricultural Chemists. 1960. Official methods of analysis. Ed. 9. Washington, D. C. p. 12-13.

4. Awan, A. B. 1964. Efecto de cal en la disponibilidad de fosforo en los suelos de El Zamorano. Ceiba 10: 62-67.

5. Awan, A. B. 1964. Influence of mulch on soil moisture, soil temperature and yield of potatoes. Amer. Potato J. 41 (10): 337-339.

6. Awan, A. B. 1965. Efecto de la fertilización con potasio sobre el rendimiento y acame del maiz. Ceiba 11: 90-93.

7. Awan, A. B. 1965. The effect of fertilization on potato yields. Ceiba 11: 18-21.

8. Barrow, N. J. 1961. Phosphorus in soil organic matter. Soil and Fert. 24: 169-173.

9. Bates, J. A. R., and T. C. N. Baker. 1960. Studies on a Nigerian forest soil: II. The distribution of phosphorus in the profile and in various soil fractions. J. Soil Sci. 11: 257-265.

10. Bennett, W. F., J. Pesek, and J. Hanway. 1962. Effect of nitrogen on phosphorus absorption by corn. Agron. J. 54: 437-442.

11. Blake, G. R. 1965. Particle density. In Methods of Soil Analysis. Part I. Amer. Soc. Agron. Publishers, Madison, Wisc. p. 374-390.

12. Bornemisza, E. 1966. El fósforo orgánico en suelos tropicales. Turrialba 16: 33-38.

13. Bouma, D. 1960. The effect of ammonium sulfate usage on the availability of soil phosphorus to citrus. Aust. J. Agr. Res. 11: 292-303.

14. Bouyoucos, G. J. 1936. Directions for making mechanical analyses of soil by the hydrometer method. Soil Sci. 42: 225-229.

15. Bray, R. H., and L. T. Kurtz. 1945. Determination of total organic and available forms of phosphorus in soils. Soil Sci. 59: 39-45.

16. Broadbent, F. E. 1957. Organic matter. In U. S. D. A. Yearbook, Soil. p. 151-157.

17. Bruce, R. C., and E. H. Tyner. 1960. Timing nitrogen applications for maize in tropical region characterized by wet and dry seasons. Int. Congr. Soil Sci. Trans. 7th (Madison, Wisc., USA) 3: 504-509.

18. Caldwell, A. C. 1960. The influence of various nitrogen carriers on the availability of fertilizer phosphorus to plants. Int. Congr. Soil Sci. Trans. 7th (Madison, Wisc., USA) 3: 517-525.

19. Clement, C. R., A. J. Heard, W. Stiles, and T. E. Williams. 1961. The measurement of the effect of leys on soils. In Research Techniques in use at the Grassland Research Institute Hurley. Commonwealth Agricultural Bureaux. p. 107-109.

20. Cole, C. V., D. L. Grunes, L. K. Porter, and S. R. Olsen. 1963. The effects of nitrogen on short-term phosphorus adsorption and translocation in corn (Zea mays). Soil Sci. Soc. Amer. Proc. 27: 671-674.

21. Dahnke, W. C., J. L. Malcolm, and M. E. Menendez. 1964. Phosphorus fractions in selected soil profiles of El Salvador as related to their development. Soil Sci. 98: 33-38.

22. Das, A. C. 1963. Utilization of insoluble phosphates by soil fungi. J. Indian Soc. Soil Sci. 11: 203-207.

23. Dev, G. 1964. Influence of nitrogen on the availability of fertilizer phosphorus. Nature 203: 899.

24. DeWit, C. T. 1953. A physical theory on placement of fertilizer. Versl. Landbouwk. Onderz. 59.4. 71 p.

25. D'Hoore, J. L. 1964. Soil Map of Africa. Explanatory monograph. Commission for technical co-operation in Africa. Joint Project 11. Lagos, Nigeria. p. 77-83.

26. Dormaar, J. F., and J. W. Ketcheson. 1960. The effect of nitrogen form and soil temperature on the growth and phosphorus uptake of corn plants grown in the greenhouse. Can. J. Soil Sci. 40: 177-184.

27. Dudal, R. 1963. Dark clay soils of tropical and sub-tropical regions. Soil Sci. 95: 264-270.

28. Food and Agriculture Organization of the United Nations. 1965. Dark clay soils of tropical and sub-tropical regions. Edited by R. Dudal. Rome. FAO Agricultural Development Paper No. 83. 161 p.

29. Goswami, N. N., and N. P. Datta. 1961. Tracer studies on the decomposition of C^{14} and P^{32} tagged organic matter and nutrient availability relationships in soils. J. Indian Soc. Soil Sci. 9: 269-279.

30. Grunes, D. L. 1959. Effect of nitrogen on the availability of soil and fertilizer phosphorus to plants. Advance. Agron. 11: 369-396.

31. Grunes, D. L. 1960. Nitrogen affects the relative availability of soil and fertilizer phosphorus to plants. Int. Congr. Soil Sci. Trans. 7th (Madison, Wisc., USA) 3: 307-313.

32. Hammond, L. C., and W. K. Robertson. 1965. Effect of fertilizer placement on P and K uptake by corn. Soil and Crop Sci. Soc. Fla. Proc. 25: 226-231.

33. Hardy, F. 1928. An index of soil texture. J. Agr. Sci. 18: 252-256.

34. Hardy, F. 1947. Effects of increasing phosphate dosages on the utilization of nitrogen. Trop. Agriculture, Trin. 24: 9-18.

35. Hardy, F. 1948. Phosphate deficiency in some West Indian soils as revealed by pot tests. Trop. Agriculture, Trin. 26: 85-92.

36. Hardy, F. 1948. The phosphate status of some British Guiana sugar-cane soils as assessed by a simple pot test. Trop. Agriculture, Trin. 26: 43-47.

37. Hardy, F., and C. W. Hewitt. 1948. A preliminary investigation into nitrification in British Guiana sugar-cane soils. Trop. Agriculture, Trin. 25: 38-40.

38. Hawkins, R. H., and G. W. Kunze. 1965. Phosphate fractions in some Texas Grumusols and their relation to soil weathering and available phosphorus. Soil Sci. Soc. Amer. Proc. 29: 650-656.

39. Holdridge, L. R. 1959. Simple method for determining potential evapotranspiration from temperature data. Science 130 (3375): 572.

40. John, M. K., N. P. Sprout, and C. C. Kelley. 1965. The distribution of organic phosphorus in British Columbia Soils and its relationship to soil characteristics. Can. J. Soil Sci. 45: 87-95.

41. Jones, T. A. 1957. Nitrogen studies on the irrigated soils of the Sudan Gezira. J. Soil Sci. 8: 211-224.

42. Jones, T. A. 1958. Carbon studies on the irrigated soils of the Sudan Gezira. J. Soil Sci. 9: 272-276.

43. Jones, T. A. 1958. Nitrogen studies on the irrigated soils of the Sudan Gezira. J. Soil Sci. 9: 267-271.

44. Kabaara, A. M. 1964. Nitrate studies in a fertilizer experiment in Sukumaland, Tanganyika. E. Afr. Agr. For. J. 30: 142-48.

45. Kaila, A. 1963. Organic P in Finnish Soils. Soil Sci. 95: 38-44.

46. LeClerg, E. W., W. H. Leonard and A. G. Clark. 1962. Field Plot Technique. 2nd. Ed. Burgess Publishing Co., Minneapolis, Minn. p. 144-146, 161-183.

47. Malavolta, E., H. P. Haag, F. A. F. Mello, and M. O. C. Brasil. 1962. On the Mineral Nutrition of Some Tropical Crops. International Potash Institute, Berna, Switzerland. p. 15-18.

48. Martin, J. K. 1964. Soil organic phosphorus: I. Methods for the extraction and partial fractionation of soil organic phosphorus. New Zealand J. Agr. Res. 7: 723-735.

49. Martin, J. K. 1964. Soil organic phosphorus: II. The nature of soil organic phosphorus. New Zealand J. Agr. Res. 7: 736-749.

50. Martin, J. K. 1964. Soil organic phosphorus: III. Patterns of organic phosphorus in a series of representative New Zealand soils. New Zealand J. Agr. Res. 7: 750-760.

51. Mehta, B. V., and J. M. Patel. 1963. Some aspects of phosphorus availability in Gujarat soil. J. Indian Soc. Soil Sci. 11: 151-157.

52. Miller, M. H., and G. C. Ashton. 1960. The influence of fertilizer placement and rate of nitrogen on fertilizer phosphorus utilization by oats as studied using a central composite design. Can. J. Soil Sci. 40: 157-167.

53. Miller, M. H., and A. J. Ohlrogge. 1958. Principles of nutrient uptake from fertilizer bands: 1. Effect of placement of nitrogen fertilizer on the uptake of band-placed phosphorus at different soil phosphorus levels. Agron. J. 50: 95-97.

54. Nye, P. H., and M. H. Bertheux. 1957. The distribution of phosphorus in forest and savannah soils of the Gold Coast and its agricultural significance. J. Agr. Sci. 49: 141-159.

55. Nye, P. H., and D. J. Greenland. 1960. The soil under shifting cultivation. Tech. Communication No. 51. Commonwealth Bureau of Soils, Harpenden. p. 112-113.

56. Olsen, S. R., and L. A. Dean. 1965. Phosphorus. In Methods of Soil Analysis. Part II. Amer. Soc. Agron. Publishers, Madison, Wisc. p. 1035-1040.

57. Olson, R. A., and A. F. Dreier. 1956. Nitrogen, a key factor in fertilizer phosphorus efficiency. Soil Sci. Soc. Amer. Proc. 20: 509-514.

58. Patel, J. M., and B. V. Mehta. 1961. Soil phosphorus fractionation studies. Soil Sci. Soc. Amer. Proc. 25: 190-192.

59. Patel, J. M., and B. V. Mehta. 1961. Studies in soil organic phosphorus fractions. J. Indian Soc. Soil Sci. 9: 63-69.

60. Peech, M., L. T. Alexander, L. A. Dean, and J. F. Reed. 1947. Methods of soil analysis for soil fertility investigations. U. S. D. A. Circ. No. 757. 25 p.

61. Rai, A. K., C. R. Prasad, and S. C. Mandal. 1963. Effect of liming on availability of phosphate in an acid red loam soil. J. Indian Soc. Soil Sci. 11: 137-140.

62. Rao, S. W. V. B., P. D. Bajpai, J. P. Sharma and B. V. Subbiah. 1963. Solubilization of phosphates by phosphorus solubilizing organisms using P^{32} as tracer and the influence of seed bacterization on the uptake by the crop. J. Indian Soc. Soil Sci. 11: 210-218.

63. Rennie, D. A., and R. J. Soper. 1958. The effect of nitrogen additions on fertilizer phosphorus availability. J. Soil Sci. 9: 155-167.

64. Robertson, W. K., P. M. Smith, A. J. Ohlrogge, and D. M. Kinch. 1954. Phosphorus utilization by corn as affected by placement and nitrogen and potassium fertilization. Soil Sci. 77: 219-226.

65. Roche, A. 1959. L'action de phosphates insolubles sur les groupes microbiens telluriques. Ann. Inst. Pasteur 96: 607-613.

66. Russell, E. J. 1961. Soil conditions and plant growth. 9th Ed. Longmans, Green and Co., London. p. 475-476.

67. Saxena, S. N. 1963. An improved procedure for the extraction of organic phosphates in soil. J. Indian Soc. Soil Sci. 11: 137-144.

68. Sen, A., P. M. Mehta, and R. B. Rewari. 1960. Relationship of the values of available phosphate as determined by chemical methods with nitrogen fixation in soils by Azotobacter. J. Indian Soc. Soil Sci. 8: 65-69.

69. Sengupta, M. B. and A. H. Cornfield. 1963. Effect of calcium carbonate content and soluble phosphate on the mineralization of organic phosphorus in calcareous soil. J. Indian Soc. Soil Sci. 11: 373-378.

70. Sierra, F. A. 1959. A comparison of the amount of phosphorus removed from different soils by extracting solutions. (Unpublished M. S. Thesis, Univ. of Fla., Gainesville.)

71. Snedecor, G. W. 1956. Statistical methods applied to experiments in agriculture and biology. Iowa State Coll. Press., Ames, Iowa. 534 p.

72. Soil Survey Staff. 1960. Soil classification, a comprehensive system, 7th approximation. Soil Conservation Service, USDA. 265 p.

73. Swaby, R. J., and J. Sherber. 1958. Phosphate-dissolving micro-organisms in the Rhizosphere of legumes. In Nutrition of the Legumes. Academic Press Inc., New York. p. 289-294.

74. Thompson, L. M., C. A. Black, and J. A. Zoellner. 1959. Occurrence and mineralization of organic phosphorus in soils, with particular reference to associations with nitrogen, carbon, and pH. Soil Sci. 77: 185-196.

75. Truog, E. 1930. The determination of the readily available phosphorus of soils. J. Amer. Soc. Agron. 22: 874-882.

76. Ulrich, A., D. Ririe, F. J. Hills, A. G. George, M. D. Morse, and C. M. Johnson. 1959. Plant analysis and analytical methods. Bull. 766. Calif. Agr. Exp. Sta. 77 p.

77. Van Diest, A., and C. A. Black. 1959. Soil organic phosphorus and plant growth. I. Organic phosphorus hydrolyzed by alkali and hypobromite treatments. Soil Sci. 87: 100-104.

78. Van Diest, A., and C. A. Black. 1959. Soil organic phosphorus and plant growth. II. Organic phosphorus mineralized during incubation. Soil Sci. 87: 145-154.

79. Vine, H. 1940. Physical properties of soils that affect plant nutrition. Trop. Agriculture, Trin. 27: 106-109.

80. Vomocil, J. A. 1965. Porosity. In Methods of Soil Analysis. Part I. Amer. Soc. Agron. Inc. Publishers, Madison, Wisc. p. 299-314.

81. Walkely, A. 1947. A critical examination of a rapid method for determining organic carbon in soils. Soil Sci. 63: 251-264.

82. Wheeler, J. L. 1960. A response to phosphate on an all-grass sward. J. Br. Grassld Soc. 15: 300-301.

83. Yuen, S. H., and A. G. Pollard. 1957. The availability of soil phosphate: IV. The effect of nitrogen on the utilization of phosphate by Italian ryegrass. J. Sci. Fd Agr. 8: 475-482.

BIOGRAPHICAL SKETCH

Carlos F. Burgos was born on February 6, 1937, at San Salvador, El Salvador. In November, 1955, he graduated from Instituto Nacional High School. In March 1959, he received the diploma of Agronomo from the Escuela Agricola Panamericana in Honduras. He was awarded the Dr. Wilson Popenoe scholarship to continue his undergraduate work. In September of 1959, he enrolled in the College of Agriculture at the University of Florida and received the degree of Bachelor of Agriculture in 1961. The same year, he enrolled in the Graduate School of the University of Florida. Mr. Burgos worked as a research assistant in the Department of Soils from 1961 to 1962. In August, 1962, he received the degree of Master of Science in Agriculture. From May, 1963, to August, 1964, he taught at the Escuela Agricola Panamericana. In August, 1964, he was granted a scholarship by the Rockefeller Foundation to pursue his work toward the degree of Doctor of Philosophy.

Carlos F. Burgos is married to the former Sara M. Todd and is the father of two children. He is a member of Alpha Zeta, Gamma Sigma Delta and Phi Kappa Phi honorary fraternities.

This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Agriculture and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

April 22, 1967

H L Thornton

for Dean, College of Agriculture

Dean, Graduate School

Supervisory Committee:

Hugh Popenoe
Chairman

H L Thornton

J G A Fiskell

George Fritz

F L Stearns